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STATE OF CALIFORNIA
GOODWIN J. KNIGHT
GOVERNOR

PUBLICATION OF
STATE WATER RESOURCES BOARD

Bulletin No. 16

WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

June, 1955

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GOODWIN J. KNIGHT
GOVERNOR

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ADDRESS ALL COMMUNICATIONS TO THE SECRETARY

June 30, 1955

Honorable Goodwin J. Knight, Governor, and
Members of the Legislature of the
State of California

Gentlemen:

I have the honor to transmit herewith Bulletin No. 16 of the State Water Resources Board, entitled "Weather Modification Operations in California", as authorized by Chapter 1596, Statutes of 1951.

The program of investigation was conducted and Bulletin No. 16 was prepared by the Division of Water Resources of the Department of Public Works, under direction of the State Water Resources Board.

Bulletin No. 16 includes a brief description of the physical and theoretical bases of modern attempts to modify precipitation, documentation of rainmaking operations conducted in California, critical study of present documentation attesting to the effectiveness of rainmaking operations, development of objective methods of evaluating these and future operations, and recommendations concerning unequivocal determination of the effectiveness of weather modification operations.

Very truly yours,

Clair A. Hill
Chairman

ACKNOWLEDGMENT

Valuable assistance and data used in this investigation were furnished by agencies of the Federal Government, public agencies, and by private companies and individuals. This cooperation is gratefully acknowledged.

Special mention is made of the helpful cooperation of the Statistical Laboratory and the Department of Meteorology of the University of California; Messrs. Edward M. Vernon, Leslie Smith, and Ferguson Hall of the United States Weather Bureau; and the Weather Control Research Association, a nonprofit organization including in its membership nearly all persons and organizations in California interested in weather modification.

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CHAPTER I. INTRODUCTION

The continuing growth and development of the Nation is accompanied by increasing requirements for water for additional and more intensively irrigated land, for expanding industry, for growing cities, for greater recreational facilities, and for increased hydroelectric power development. As these requirements for water increase we are faced with the necessity of evaluating and comparing them with the developed water supplies and with the available water resources, of determining the quantities of supplemental water ultimately needed, and, finally, of making plans for meeting the supplemental requirements of the various areas.

A necessary and basic part of these studies consists of an assessment of the adequacy and availability of the fresh-water resources of each area and of the Nation. The fresh-water resources include precipitation in its many forms, runoff of surface streams, and underground waters. Since all of these exhibit both geographic and seasonal deficiencies and variations which are restrictive and occasionally disastrous, any developments which might increase the availability of our water resources or provide for new ones would be of the utmost national importance.

In recent years discoveries have been made and experiments performed which suggest the intriguing possibilities that control or modification of some aspects of the weather is possible, that additional precipitation might result, and that the historic climatic variability might be reduced. There is speculation that these discoveries might lead to the development of a new resource

of water. Beginning in 1946 and continuing to the present time there has been an increasing interest and activity in a field of endeavor called "rainmaking". This interest in weather modification and the application of weather modification or "cloud seeding" techniques have been world-wide.

Authorization for Investigation

As a result of public interest in the potentialities of artificial modification of precipitation and in the operations of concerns and individuals engaged in activities aimed at accomplishing this end, three laws pertaining to weather modification were enacted during the 1951 Session of the California Legislature. The first of these statutes, Chapter 1374, authorized the Riverside County Flood Control and Water Conservation District to levy taxes for the purpose of carrying on a weather modification program within the district. A second statute, Chapter 1677, now Chapter 4, Division 1, of the Water Code, provided for the licensing and reporting of weather modification activities in California. The provisions and regulations of this statute are administered by the Department of Public Works acting through the State Engineer.

The third statute, Chapter 1596, now Section 12605 of the Water Code, authorized and provided funds for an investigation of "the control of rainfall by artificial means". A sum of $50,000 was appropriated to the State Water Resources Board from the General Fund in the State Treasury to meet the costs of the investigation. An agreement between the State Water Resources Board and the State Department of Public Works acting through the agency of the State Engineer, authorizing the Division of Water

Resources to conduct the current investigation, under direction of the Board, was executed on October 1, 1951. Some additional funds were expended in connection with preliminary studies made at the specific request of the State Water Resources Board prior to the enactment of Chapter 1596, Statutes of 1951. The results of these preliminary studies proved valuable as background material to aid in planning the current investigation.

Copies of Chapters 1374, 1596, and 1677, Statutes of 1951, are included in Appendix A.

Related Investigations and Reports

There is much recent literature concerning weather modification, generally falling into two broad groups. One group describes the physical phenomenon of weather modification, and explores various theoretical hypotheses concerning this phenomenon. The other group consists of evaluations of specific weather modification operations, attempting by various means to determine the effectiveness of these operations. Both groups are somewhat speculative, although the second is much more so, depending, as it does, on cumulative and inferential evidence. Fairly comprehensive bibliographies dealing with both types of reports may be found in "Meteorological Abstracts and Bibliography", published by the American Meteorological Society, Boston, Massachusetts, with Vol. 1, No. 3, March, 1950, particularly devoted to this subject, and in the December, 1952, issue of the "Transactions" of the American Geophysical Union. The bibliography in the Transactions is incorporated in an article by Mr. Ferguson Hall, entitled "Status of Possibilities of Artificial Precipitation". Other published

reports which have come to attention during the current investigation are listed in Appendix B. Also, a fairly extensive bibliography of papers and reports on the subject of ice-crystal nuclei and sublimation particles is appended to Appendix G.

Scope of Investigation and Report

A definite program of research relative to the production and control of rainfall by artificial means was not specified in the legislation providing for the present investigation. The State Water Resources Board, at its meeting of September 7, 1951, approved a work program which, while taking cognizance of the physical and theoretical bases of weather modification and of the necessity of making further investigations in this field, placed more emphasis on investigating the effectiveness of actual experimental and commercial weather modification activities. Work on the investigation commenced in October, 1951, and continued into 1954.

Early in the course of the investigation a program of evaluation analysis was undertaken. Of the large number of experimental and commercial weather modification operations undertaken since 1946, a considerable number have been the subjects of published or unpublished reports purporting to assess the effectiveness of the operations. Examination of 12 of these reports which had been prepared prior to January, 1952, indicated large variations in the kinds of evidence and evaluations presented. The one common feature of all reports was the indirect and inferential nature of the evidence. The bases of comparison were so varied that it became clear that no unequivocal indication of results had been

discovered. It was concluded that in the case of all operations, except those subject to strict scientific control, the available evidence would continue to be indirect and inferential. For these reasons, it was decided to concentrate the current investigation on a statistical approach to the problem of evaluation.

To obtain the most competent assistance in the field of statistical analysis, services of the Statistical Laboratory of the University of California were secured, first through a contract with its director, Dr. Jerzy Neyman, as special consultant, and subsequently by the execution of a service agreement with the Laboratory. Dr. Neyman is an eminent statistician whose world-wide reputation embraces both the theoretical and practical aspects of statistical analysis. He is the author of many basic contributions to the theory of statistical inference and to the applications of statistical inference to scientific investigation and experimentation. Dr. Neyman's report as consultant formed the basis for a work program set up in a service agreement with the Statistical Laboratory, executed on January 1, 1952, and contracting for services of the staff of the laboratory until June 30, 1953. This program consisted of three phases: review and analysis of present reports and methods of evaluation; development of further methods of evaluating weather modification operations; and design of possible future plans of operation to afford more unequivocal bases for evaluation. Reports of the Statistical Laboratory are included as Appendixes C and D. The Office of Naval Research exhibited an interest in certain phases of this work of the Statistical Laboratory and contributed funds for the prosecution of these phases.

Additional assistance was obtained from Dr. Elizabeth L. Scott, Assistant Professor of Mathematics, of the Statistical Laboratory, who, as Editorial Consultant, aided in the preparation and review of the technical discussion presented in this bulletin. Dr. Scott is the author of numerous research articles on statistics and various applications of statistical methods.

In addition to studies made by the Statistical Laboratory, other similar studies were made by the Division of Water Resources, some related to the foregoing work program, and others independent of this program. These included investigation of the reliability of basic data, determinations of groupings of precipitation stations suitable for use in evaluation studies, and separate evaluations of specific weather modification operations. A state-wide survey was made to obtain data on recent weather modification operations in order to determine the extent of these operations, to aid in the separation and selection of specific areas for which evaluation studies could be made, and to enable a proper selection of target and control areas. Meteorological studies were made of the physical processes involved in the production of rainfall, both naturally and by artificial means, and other meteorological considerations were investigated as would contribute to the seccessful completion of the other phases of the investigation.

The Statistical Laboratory, in its investigation of new methods for evaluating historical weather modification operations, recommended a procedure whereby individual storms would be characterized by meteorological measurements useful in separating these storms into various categories adaptable to effective statistical

analysis. Determination of the storm characteristics used to define pertinent categories required the knowledge and experience of highly trained synoptic meteorologists. For this reason, Dr. Morris Neiburger, Professor of Meteorology at the University of California at Los Angeles, and Mr. Edward M. Vernon, then Chief Regional Forecaster for the United States Weather Bureau, with headquarters at the San Francisco Municipal Airport, San Bruno, California, were engaged as special consultants. Dr. Neiburger is an authority in the fields of dynamic and synoptic meteorology and atmospheric physics and the author of many papers in the field of meteorology. Mr. Vernon, an outstanding synoptic meteorologist with long experience in weather forecasting on the West Coast, is presently Chief of the Division of Synoptic Reports and Forecasts of the United States Weather Bureau in Washington, D. C. Each, according to his own system, outlined sets of categories and the criteria defining storm classes for use in evaluation studies. The categories were then used in certain analyses. Reports by Dr. Neiburger and Mr. Vernon are included as Appendixes E and F.

The phase of the investigation dealing with fundamental physical research into the basis of weather modification was of necessity severely limited. Preliminary studies indicated that the funds available would not permit complete investigation of all the aspects of the problem. Consequently, the work program placed more emphasis on evaluation of recent commercial weather modification activities. Some physical investigation was accomplished, however. A service agreement was executed with the Institute of Engineering Research of the University of California for the development and construction of a sublimation nuclei counter.

This instrument, essentially a modified deep-freeze unit, when operated on a regular observing schedule will provide a record of effective ice-crystal nuclei in the atmosphere. This information which is presently obtained only at Mount Washington, New Hampshire, will be valuable in future studies of cloud physics. The report of the Institute of Engineering Research is included as Appendix G. An additional activity having relation to the physical aspects of weather modification consisted of a program of observation of weather modification operations in San Diego County, undertaken during the summer and early fall of 1952. Visual and photographic data were collected, as well as precipitation records from a special rain gage network, in an effort to determine whether a commercial weather modification operation could be adapted to a controlled experiment, and to investigate by trial the problems which would be encountered in the conduct of such an experiment.

A legal report was prepared by the legal staff of the Division of Water Resources, concerning the responsibilities and liabilities involved in the creation of rainfall by artificial means, and the power of the State to regulate and control such activities. This report is included as Appendix H.

An economic report was prepared by the staff of the Division of Water Resources, concerning the possible economic results of weather modification operations. This report is included as Appendix I.

Results of the investigation are presented in this bulletin in the three ensuing chapters. Chapter II, "Theory of Weather Modification and History of Operations in California", briefly outlines outstanding discoveries and developments basic

to the present knowledge and understanding of precipitation processes. It also includes a summary of the basis and development of weather modification operations and a documentation of recent weather modification operations in California. Chapter III, "Evaluation Methods and Evaluation of Selected Operations", includes a survey and appraisal of methods used in the evaluation of weather modification operations, presents evaluations of several selected projects, and outlines an objective method for the unequivocal determination of the effectiveness of weather modification operations. Chapter IV, "Summary of Conclusions, and Recommendations", includes conclusions and recommendations resulting from the investigation and studies.

CHAPTER II. THEORY OF WEATHER MODIFICATION AND HISTORY OF OPERATIONS IN CALIFORNIA

From many cultures and in many periods of history have come indications of man's desire to change the course of the weather for his own benefit. The earliest and most primitive attempts at weather control involved the use of magic. The rain dances of various Indian tribes of the southwest are instances of the survival to modern times of this approach to the problem. However, as man came to understand the magnitude of the forces involved in the circulation of the atmosphere, he came more and more to consider himself an impotent observer, able to "talk about the weather but .... not do anything about it". Nevertheless, man's curiosity has promoted him to take measurements of various phases of the weather, beginning with readings of wind direction, precipitation, and wind intensity; later, of temperature, barometric pressure, and relative humidity; and, most recently, of characteristics of the upper atmosphere. From study and analysis of this and other relevant data, there has come a growing understanding of the nature of atmospheric circulation, and of the interrelations among various aspects of the weather.

The picture that emerges is one of amazing complexity, with wide variability in combinations of differing kinds of weather over various parts of the earth, and with constant fluctuation, from instant to instant, in these relations. However, certain principles of combination do appear to persist. In addition, there are other smaller-scale physical relations

which have either been demonstrated or, at least, set up as hypotheses to explain apparent combinations of phenomena. One of the sets of phenomena which have been investigated is the complex of relations involving the production of rain. It has always been interesting to speculate as to what differentiates a cloud from the clear air, and, even more interesting, as to what differentiates a precipitating cloud from one which retains its moisture.

History and Theory of Weather Modification

As the understanding of cloud physics grew, one of the most significant early findings was the discovery of nuclei of condensation by Coulier in 1875. Subsequently, John Aitken investigated these nuclei over a long period, and came to the conclusion that clouds consisted of minute water droplets condensed upon sub-microscopic particles of dust and other substances. The conditions for the actual process of condensation of water vapor, and the growth of droplets to cloud drop size, are the subjects of a complex study which has engaged the interest of many investigators.

Other studies have concerned the boundary conditions of clouds, and the actual mechanism of precipitation. The most prominent early students of this last matter were Tor Bergeron and W. Findeisen, both presenting their original papers in the middle 1930's. Simply stated, the mechanism for the production of rainfall, described by their research, is as follows: In most situations of heavy precipitation in the temperate zones, large cumulus clouds exist in which there is a region of temperatures between 0° C. and about -40° C., and in which there co-exist

ice-crystals, super-cooled water drops, and water vapor in a state of supersaturation. It is known that vapor pressure over an ice-crystal is much lower than over a super-cooled water drop. Therefore, if an ice-crystal is introduced into a super-cooled cloud, water vapor will be transferred from the water drops to the ice-crystal, which will grow in size and finally attain sufficient mass to fall. Further growth takes place by collision with other drops in the path of the fall. The prolongation of the precipitation process depends up n the rate at which moist air enters the cloud.

The significant aspect of the foregoing, from the point of view of weather modification, is the role of the ice-crystals. In current weather modification operations it is assumed that there are insufficient ice-crystals in the critical temperature zone to initiate and sustain the precipitation process. Two methods are generally used to increase the concentrations in great numbers. One method is to reduce the temperature of the supersaturated water drops below -39° C., the spontaneous freezing level. The other is to introduce a foreign particle which apparently performs the function of the ice-crystal. A number of different substances seem to be able to perform this latter function. However, the substance used most extensively for this purpose to date is silver iodide. The most efficient present method of reducing the temperature to the spontaneous freezing level is by the distribution of solid carbon dioxide pellets into the appropriate part of the cloud. In passing downward through the cloud, the pellets generate tremendous numbers of ice-crystals.

One of the earliest scientific investigators to propose seriously the modification of precipitation by artificial means was Louis Gathman, who in 1891 suggested liberating liquified carbonic acid gas into the air, thus cooling water vapor to produce condensation and precipitation. In this proposal Gathman seems to have come fairly close to the modern conception. Later "rainmakers", with varying misconceptions or oversimplifications of the precipitation process, used such agents as explosions, electric discharges, electrified sand, and burning chemicals, to attempt to influence rainfall. In California, Charles M. Hatfield is reported to have used the last method on numerous occasions during the first two decades of the century.

In 1930, August W. Veraart performed several experiments in Holland, releasing a mixture of water ice and dry ice from an airplane. He claimed to have increased the rain falling on the days of the experiment by a spectacular amount. The extravagant nature of Veraart's claims cast doubt on his whole undertaking. Nevertheless, his reasoning was startingly similar to the Bergeron-Findeisen scheme of the precipitation mechanism, and his use of dry ice makes secure his position as pioneer in the field of weather modification.

During World War II, Dr. Irving Langmuir and Dr. Vincent Schaefer studied the production of smoke screens and the prevention of precipitation static and icing on airplanes. These studies led to the formation in March, 1947, of Project Cirrus, a cooperative research investigation in cloud physics sponsored by the Signal Corps of the United States Army and the Office of Naval Research in consultation with the General

Electric Company. Considerable effort was devoted to experiments with various agents for modifying cloud formations and stimulating precipitation. It was found that definite changes could be made in cloud structures by dispersing solid carbon dioxide above them from an airplane. Similar changes were brought about by vaporization and burning of a solution of silver iodide in acetone. Also, both agents apparently produced visible precipitation effects under appropriate conditions.

The work done by Drs. Langmuir, Schaefer, Bernard Vonnegut, and others of the General Electric Research Laboratory excited great interest in the possibility of increasing rainfall. Experiments have been carried out by different interests in many parts of the United States as well as in a number of foreign countries. The urgent need for more rainfall has been the dominating influence in determining the location of most of the experiments. Many areas of the world, in need of increased and assured supplies of water, have since early 1947 been the scenes of weather modification operations. Other operations have been conducted to suppress lightning, prevent hail, and to disperse fog. Many of these operations rapidly took on the character of commercial enterprises and have remained so to the present.

A brief survey made in connection with the current investigation indicated that during 1951 almost 20 per cent of the total area of the United States was the target for weather modification operations, and it is possible that a much greater area was affected. It is probable that a somewhat smaller area was involved in 1952-53. There was, however, a renewal of activity in California in 1953-54 and 1954-55.

History of Weather Modification in California

The history of documented weather modification operations in California can be divided into two periods; the first or earlier period including all operations conducted prior to the announcement in 1946 of successful dry-ice seeding by Drs. Langmuir and Schaefer, and the recent period including operations conducted following this announcement. As far as has been determined, the operations during the first period are essentially limited to those of Mr. Charles M. Hatfield.

Operations Prior to 1946

A history of weather modification operations in California would be incomplete without at least brief mention of the activities of Mr. Charles M. Hatfield during the first two decades of the century. A review of newspapers and periodicals reveals that in early 1904 a group of Los Angeles merchants contracted with Mr. Hatfield to produce one inch of rain. Subsequently, it is stated, he began operations on February 2nd, and by February 9th a total of 1.64 inches of rain had fallen. In 1905 the same group contracted for 18 inches of rain, and it is revealed that 19.19 inches fell during the time covered by the contract. Seven years later, in 1912, it is reported that Mr. Hatfield contracted with ranchers and businessmen in Hemet Valley, and that "results were satisfactory". In January, 1916, Mr. Hatfield, in anticipation of a contract with the City of San Diego, set up his equipment and began operations with the evident purpose of filling Lake Morena Reservoir on Cottonwood Creek. On January 27th a storm occurred, bringing 16.30 inches of rain in 24 hours, which not only filled Lake Morena Reservoir but burst a dam at Lower

Otay Reservoir, sending a destructive wall of water down the Otay River, resulting in great damage as well as loss of life. Following this occurrence there is no further record of Mr. Hatfield's operations in California. The equipment or techniques used by Mr. Hatfield are not known; however, it is reported that his operations included the burning and boiling of various chemicals.

Operations Subsequent to 1946

In connection with the current investigation, a statewide survey was made to obtain data on recent weather modification operations in California. Data for the precipitation seasons from 1946-47 through 1950-51 were obtained by field canvass. Data for subsequent seasons are and will continue to be available in the files of the Division of Water Resources under the provisions of Chapter 4, Division 1, of the Water Code, which, as indicated previously, provides for the regulation and licensing of weather modification operations. A list of operations conducted during each season from 1946-47 through 1951-52, showing the contracting organization, contractor, area of operation by project location designation and by hydrographic unit, period of operation, nucleating agent, and other information, is presented in Table 1. Daily summaries of the operations are shown on Plates 1 through 5, entitled "Log of Weather Modification Operations". Numbers designating the location of the various projects refer to hydrographic units as shown on Plate 6, entitled "Hydrographic Divisions in California". Project 5-42 for example, is in the Central Valley, designated hydrographic area

number 5, and is further located as being in hydrographic unit number 42. Division of the State into hydrographic units as shown on Plate 6 is the same as that used in Bulletin No. 2, "Water Utilization and Requirements of California", a publication of the State Water Resources Board.

Table 1 indicates that recent activities in weather modification in California began during the winter of 1947-48, about one year following the announcement of the results of the dry-ice seeding experiments performed by Drs. Langmuir, Schaefer, Vonnegut, and others of the General Electric Laboratory at Schenectady, New York. In November, 1946, Dr. Langmuir and Dr. Schaefer claimed some success in the production of snow as a result of seeding supercooled clouds with dry ice. In response to the publicity given to these experiments, and as a result of the prolonged period of subnormal water supply and the consequent shortage of water, there were a number of aircraft-seeding flights in the southern part of the San Joaquin Valley and in southern California during the winter of 1947-48. Many of these early trials were made by private individuals for observation of the novel results. Data are sketchy for these trials, as almost no records were kept. The seeding was done from the air, using dry-ice pellets or a water spray, and in most cases the aircraft used were furnished by local airports or by crop dusting firms. It is reasonable to assume, although no records are available nor was any evidence found, that prior to the 1947-48 operations there were at least some similar experiments during the 1946-47 rainfall season, immediately following the announcements of Dr. Langmuir and Dr. Schaefer.

TABLE 1

RECENT WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

Client	Contractor	Area	Hydrographic unit	Period	Nucleating agent	Remarks
		1947-48 SEASON				
Individual pleasure flights	----	East slope of Coastal Range west of Bakersfield	5-31 5-36 5-37	Nov., 1947 through March, 1948	CO_2	8-10 flights
Ranchers in vicinity of Bakersfield	Atwood Crop Dusters, Bakersfield	Over ranches near Bakersfield	5-32 5-37	Early 1948	CO_2, H_2O	Several flights
Individual pleasure flight	L. Lasner, Pasadena	South slope of Sierra Madre near Pasadena	4-4	Feb. 2, 1948	CO_2	1 flight
Elsinore Rain Committee, Elsinore	E. L. Medlicott, Elsinore	Lake Elsinore watershed	4-5	Feb. 2,1948 to Feb. 28, 1948	CO_2, H_2O	5 flights
California Electric Power Company, Riverside	California Electric Power Company, Riverside	Bishop Creek watershed	6-9	Feb.2,1948 to June 7, 1948	CO_2, AgI	28 flights
Bakersfield Air Park, Bakersfield	Elnore Rudnick, Bakersfield	Vicinity of Bakersfield	5-32 5-37	Feb.3, 1948 to Feb. 22, 1948	CO_2, H_2O	12 flights
Bear Valley Mutual Water Company, Redlands	Precipitation Control Company, Phoenix	Big Bear Lake watershed	4-5	Mar.13,1948 to Apr. 4, 1948	CO_2	18 flights
A. L. Hannah, Hemet Airport, Hemet	A. L. Hannah, Hemet Airport, Hemet	West slope of San Jacinto Mountains near Riverside	4-5	Apr. 3, 1948	CO_2	4-6 flights
----	----	Lower Salinas Valley	3-5	Spring 1948	----	----

TABLE 1

RECENT WEATHER MODIFICATION OPERATIONS IN CALIFORNIA (continued)

Client	Contractor	Area	Hydrographic unit	Period	Nucleating agent	Remarks
			1948-49 SEASON			
Vista Irrigation District, Vista	Water Resources Development Corporation, Pasadena	Lake Henshaw watershed	4-8	Aug.4, 1948 to Mar. 24, 1949	CO_2, H_2O	14 flights
California Electric Power Company, Riverside	California Electric Power Company, Riverside	Bishop Creek watershed	6-9	Oct. 11,1948 to May 19, 1949	CO_2	44 flights
Individual flights	----	Santa Barbara	3-11 3-12	Winter 1948-49	CO_2	----
Individual flights	----	Ventura	4-1 4-2	Winter 1948-49	CO_2	----
Individual flights	----	San Diego	4-9 4-10	Winter 1948-49	CO_2	----
United States Weather Bureau	United States Weather Bureau	Colfax Divide	5-13 5-15	Jan.14, 1949 to May 2, 1949	AgI	56 operations
			1949-50 SEASON			
California Electric Power Company, Riverside	California Electric Power Company, Riverside	Bishop Creek watershed	6-9	Nov.9, 1949 to May 27, 1950	CO_2, AgI	23 flights
Carrisa Corporation, Taft	Precipitation Control Company, Phoenix	Carrizo Plain	5-31 5-36	Mar.25,1950 and Apr. 8, 1950	AgI, SO_3	2 flights

TABLE 1

RECENT WEATHER MODIFICATION OPERATIONS IN CALIFORNIA (continued)

Client	Contractor	Area	Hydrographic unit	Period	Nucleating agent	Remarks
Temescal Water Company, Corona	Temescal Water Company, Corona	Temescal Wash and Santa Ana River watersheds	4-5	Apr.7, 1950 to May 24, 1950	AgI	7 operations
		1950-51 SEASON				
California Electric Power Company, Riverside	California Electric Power Company, Riverside	Bishop Creek watershed	6-9	July 4,1950 to May 19, 1951	CO_2, AgI	46 flights
Temescal Water Company, Corona	Temescal Water Company, Corona	Temescal Wash and Santa Ana River watersheds	4-5	July 6,1950 to Sept. 6, 1950	AgI	3 operations
Carrisa Corporation, Taft	Precipitation Control Company, Phoenix	Carrizo Plain	3-4 3-9 5-31 5-36 5-44	Oct.26,1950 to May 3, 1951	AgI, SO_3	41 flights
Kern County	Precipitation Control Company, Phoenix	Bakersfield-Taft area	5-37	Oct.30,1950 to Apr. 28, 1951	AgI, SO_3	24 flights
Southern Sierra Corporation, Porterville	Precipitation Control Company, Phoenix	Kern and Tule River watersheds	5-32 5-33 5-38	Nov.13,1950 to Apr. 30, 1951	AgI, SO_3	41 flights
Santa Ana Weather Corporation, Corona	John Battle and Precipitation Control Company, Phoenix	Santa Ana River watershed	4-5	Nov.13,1950 to Apr. 23, 1951	AgI, CO_2	21 operations
City of Santa Barbara and Montecito County Water District	North American Weather Consultants, Pasadena	Watersheds above Santa Barbara	3-12	Dec.26,1950 to Apr. 29, 1951	AgI	16 operations

TABLE 1

RECENT WEATHER MODIFICATION OPERATIONS IN CALIFORNIA (continued)

Client	Contractor	Area	Hydrographic unit	Period	Nucleating agent	Remarks
Antelope Valley Water Development Corporation, Lancaster	Water Resources Development Corporation, Pasadena	Antelope Valley	6-12	Jan.10,1951 to Apr. 30, 1951	AgI	38 operations
Southern California Edison Company, Los Angeles	North American Weather Consultants, Pasadena	San Joaquin River watershed	5-45	Jan.29,1951 May 18, 1951	AgI	31 operations
City of San Diego	North American Weather Consultants, Pasadena	Watersheds above San Diego	4-9 4-10	Feb.12,1951 to Apr. 29, 1951	AgI	12 operations
Placer County Farm Labor Cooperative, Newcastle	Placer County Farm Labor Cooperative, Newcastle	Auburn-Grass Valley area	5-13 5-15	Mar.20, 1951 to May 26, 1951	not known	14 operations
		1951-52 SEASON				
United Air Lines, Inc.	Weather Control, Medford	Arcata and vicinity	1-10 1-12	Oct.10,1951 to Oct. 31, 1951	not known	10 operations
Southern Sierra Corporation, Porterville	Precipitation Control Company, Phoenix	Kern and Tule River watersheds	5-32 5-33 5-38	Oct.24,1951 to Mar. 7, 1952	AgI, SO_3	37 flights
Kern County	Precipitation Control Company, Phoenix	Bakersfield-Taft area	5-37	Oct.24,1951 to Mar. 10, 1952	AgI, SO_3	24 flights
Southern California Edison Company, Los Angeles	North American Weather Consultants, Pasadena	San Joaquin River watershed	5-45	Nov.10,1951 to Mar. 7, 1952	AgI	42 operations

TABLE 1

RECENT WEATHER MODIFICATION OPERATIONS IN CALIFORNIA (continued)

Client	Contractor	Area	Hydrographic unit	Period	Nucleating agent	Remarks
San Diego County Weather Corporation, Escondido, and Santa Ana River Weather Corporation, Corona	John A. Battle, Beaumont	San Diego County and Santa Ana River watershed	4-5 4-8 4-9 4-10	Nov.18,1951 to Mar. 16, 1952	AgI	26 operations
Santa Barbara County Water Agency, Santa Barbara	North American Weather Consultants, Pasadena	Santa Barbara County	3-10 3-11 3-12	Nov.19,1951 to Apr. 25, 1952	AgI	32 operations
California Electric Power Company, Riverside	California Electric Power Company, Riverside	Bishop Creek watershed	6-9	Nov. 21, 1951	AgI	1 operation
Antelope Valley Water Development Corporation, Lancaster	North American Weather Consultants, Pasadena	Antelope Valley	6-12	Dec.1, 1951 to Apr. 10, 1952	AgI	28 operations
Santa Clara County Weather Corporation, San Jose	Weather Modification Company, Beaumont	Santa Clara County	2-7	Dec. 1, 1951 to Mar. 24, 1952	AgI, CO_2	40 operations
Carrisa Corporation, Taft	Precipitation Control Company, Phoenix	Carrizo Plain	5-31 5-36	Dec.10,1951 to Mar. 15, 1952	AgI, SO_3	34 flights
Ventura County Cloud Seeding Corporation, Oxnard	P. J. Murray, Oxnard	Ventura County	4-1 4-2	Jan. 6, 1951 to Jan. 17, 1952	AgI	6 operations
Placer County Farm Labor Cooperative, Newcastle	Placer County Farm Labor Cooperative, Newcastle	Auburn-Grass Valley area	5-13 5-15	Mar. 20,1952 to June 26, 1952	not known	16 operations

Beginning in February, 1948, two weather modification programs were organized, one in the Lake Elsinore area in Riverside County, and a second operation by the California Electric Power Company in the Bishop Creek watershed in the Owens Valley. This last project has, except for an interruption in 1951-52, been in continuous operation since that time. A third program by the Bear Valley Mutual Water Company in the vicinity of Big Bear Lake in the upper watershed of the Santa Ana River began in March, 1948. Table 1 shows that only two organized operations were conducted in 1948-49, one for the Vista Irrigation District in the Lake Henshaw watershed in San Diego County, and the other the continuing program of the California Electric Power Company. During the 1949-50 season there were again three programs, that of the California Electric Power Company, one in the Carrizo Plain west of Bakersfield in the southern San Joaquin Valley by a group of dry-farm ranchers organized as the Carrisa Corporation, and a program of the Temescal Water Company in southern California.

The available information, as presented in Table 1, indicates that the first three seasons, 1947-48, 1948-49, and 1949-50, witnessed a quick interest in the new science followed by a decline in activity. The lapse was probably an organizational lag, during which time it was found that more elaborate, better equipped organizations, and adequate methods of financing would be required. Consequently, in 1950-51 there was a sudden renewal in activity, with 15 organized programs scattered through the southern two-thirds of the State, from Placer County on the north to San Diego County on the south. During 1951-52 the same high level of activity was maintained, with 12 programs and some

adjustment and consolidation of program areas. During this season about 12 per cent of the area of the State was the target for weather modification operations. It is estimated that the total amount of money involved in these contracts was about $200,000. During the 1952-53 season six operations were discontinued and one new operation was undertaken. The new operation, in the watersheds of the Stanislaus and Mokelumne Rivers by the Pacific Gas and Electric Company, emphasizes the current interest of hydroelectric utilities in weather modification. Along the West Coast these companies are exploring the possibilities of increasing their assured water supply through weather modification techniques, aimed at augmenting the snowpack on the watersheds above their hydroelectric power plants. During the 1953-54 and the 1954-55 seasons there were 11 and 12 programs, respectively.

An inspection of these eight seasons of record indicates that weather modification operations are now being conducted on a sustained basis, and that electric utility companies and numerous volunteer groups and organized districts are now including such operations as a part of their water development and conservation programs.

CHAPTER III. EVALUATION METHODS AND EVALUATION OF SELECTED OPERATIONS

It has been pointed out that during recent years widespread weather modification activities have been conducted in California. A similar situation has prevailed throughout much of the rest of the United States and in some foreign countries. A great number of these operations have been the subjects of published or unpublished reports purporting to assess the results. However, there is not at the present time any general agreement concerning the effectiveness of these endeavors. In fact, the public statements of investigators reveal a sharp division, namely, between those claiming successful operations and those who stoutly maintain that the effectiveness of the operations was not established.

It appears, therefore, that it is still an open question as to whether it is possible to modify precipitation to advantage or benefit. It is important, however, to assess the potentialities of weather modification. In the first place, it is becoming increasingly apparent that the arid regions must undertake the development of all of their water resources, and the possibility that weather modification presents a new resource of water should not be overlooked. In the second place, the positive claims of the rain makers in the past several years have painted a bright picture of large quantities of water readily available at low cost. As a result, in some water-deficient areas attention and efforts have probably been diverted from the planning and completion of proven water conservation projects. This distraction, if based on a fiction, is delaying

proper water conservation development. Most of the emphasis in connection with the current investigation, therefore, was placed upon the development of methods of appraisal and evaluation of weather modification operations. In view of the uncertain findings of the past reports studied, and of the inadequate data available for use in making an appraisal of the effectiveness of weather modification operations, major emphasis was placed on a statistical approach in the studies to be undertaken.

At the beginning of the investigation the possibility was considered that if the evaluation reports already made by other agencies and groups were assembled and analyzed, they would be found to demonstrate the effectiveness of cloud seeding. With this in mind, a program of analysis of these evaluations was undertaken and continued throughout the investigation. This program yielded valuable data relative to the sensitivity and appropriateness of the various evaluation techniques, and indicated the direction to be taken in the present investigation so as to avoid demonstrated pitfalls. The several methods employed by other investigators are described and evaluated in general terms later in this chapter.

As has been stated, Dr. J. Neyman, Director of the Statistical Laboratory, University of California, was appointed as a special consultant to recommend and outline a program of statistical investigation of weather modification. Dr. Neyman's report formed the general basis of the statistical evaluation program, the major part of which was carried out at the Statistical Laboratory. Reports of the Statistical Laboratory are included as Appendixes C and D. Further work on evaluations

of specific weather modification operations was also done by the Division of Water Resources, in cooperation with the Statistical Laboratory. Results of both programs are presented and discussed briefly in this chapter.

The several methods used in prior evaluation studies are examined critically and in some instances the conscientious effort of some evaluators may appear to suffer. It is not, however, the intent of this study to criticize the early evaluation work on the basis of knowledge gained after subsequent detailed study. In any case, the pioneer efforts of the earliest investigators in scientific fields are seldom the last work. For this reason, and since the results of evaluation studies have been and are being used to sell a commercial service, ethics would require that better methods when revealed should be employed in future studies.

Methods Employed in Evaluation Reports by Other Agencies

The physical precipitation processes in the free atmosphere and their modification by cloud seeding activities are extremely difficult, if not impossible, to demonstrate under natural conditions. For this reason, evaluations of the effectiveness of weather modification operations have often been of an indirect or circumstantial nature. In addition, there is no established body of criteria for determining the effectiveness of cloud seeding. As a result, several different evaluation techniques have been used in the past. These techniques, separated according to method of analysis, fall into one or the other

of the general classifications of "visual evidence" or "quantitative evaluations".

Visual Evidence

A large number of the reports reviewed presented visual evidence, consisting specifically of descriptions of occurrences of rainfall simultaneously with or shortly following deposition of seeding agents.

Many of the earlier studies depended almost entirely upon visual and photographic evidence. Typical were those of Project Cloud Physics, in which the United States Air Force, the National Advisory Committee for Aeronautics, and the United States Weather Bureau cooperated in a series of experiments during 1948 and 1949 aimed at determining the effects of seeding clouds of various types. In these earlier studies the observers often made detailed descriptions of the clouds, of the sequence of modification of the clouds, and of the occurrence of precipitation following seeding. The observations made in connection with Project Cloud Physics were interpreted as being generally negative, that is, the cloud modification did not result in increased precipitation. In other experiments, including earlier field tests under Project Cirrus, the results were interpreted as positive. Much other visual and psychological evidence has been collected. Photographs and radar echoes have indicated that there apparently was precipitation from cumulus clouds seeded by solid carbon dioxide or by silver iodide smoke.

In the case of claims and contentions based on visual evidence, there is no known proof that precipitation would not

have occurred or that the clouds would not have dissipated in the absence of seeding. This proof might be established if simultaneous observations were made on several clouds selected to be seeded or left unseeded on some pre-established and objective principle. An exception to the foregoing statements is the photographic evidence which can apparently be accepted as documentary evidence that certain clouds can be modified by seeding. For instance, clearing patterns have been produced in stratus cloud layers corresponding to the flight lines of planes which were dispensing dry ice pellets. In any case, this evidence is not effective in establishing any more than the particular modifications actually observed.

Descriptions of the visual effects of seeding operations might be considered helpful to operators interested in improving seeding techniques, but they contain little information useful for evaluation purposes, since they are not quantitative.

Quantitative Evaluations

As weather modification operations became widespread, visual evidence proved to be even less adequate for evaluation because it could not express the experience over large areas and long periods. The writers of most evaluation reports have relied, therefore, upon quantitative data in various forms to substantiate their assessment of the effects of cloud seeding. The methods of evaluation reviewed in connection with the current investigation, and which may be considered quantitative in their nature, have relied in general on comparisons of precipitation

in seeded areas with historic precipitation in the same areas, and on comparisons with simultaneous precipitation in adjacent areas.

Evaluation Based on Historical Data. Frequently a comparison is made between the amounts of rainfall occurring during cloud seeding operations and historical rainfall amounts in the same area. The claim is then made that the precipitation during and following seeding, if greater than that within the past recollection of the observer, must have resulted from the operation. The probability of natural occurrence of the particular amount of rain, without the seeding, is ignored.

A more sophisticated method of analysis using historical data is based upon the selection and use for comparison of analogues, or similar historic storms. In practice, the evaluator searches through historical weather maps to find a storm similar to one which has been seeded. There have been developed elaborate systems of storm classification which, when used together with an extensive weather map library, enable the selection of apparently similar storms. A comparison is then made between rainfall amounts from the seeded storm and from the similar unseeded storm. Examination of evaluations based on the use of analogues revealed that the similarity of the analogue to the seeded storm, based generally on a comparison of isobar patterns, was often more apparent than real. Furthermore, even after the selection of one particular analogue for comparison with a particular seeded storm, it was likely that many other

similar storms had not been considered, some of which might have resulted in more rain and some less than the selected analogue. It is upon this last point, namely, the comparison of a particular seeded storm with only one historical storm, that the major criticism of the analogue evaluation is based.

Evaluation Based on Comparative Data. In many weather modification evaluation reports, comparative evidence was produced to determine the portion of the precipitation attributable to cloud seeding, or to determine the probability of getting a particular amount of rain naturally. The quantitative expressions varied considerably from report to report, but the evidence was generally presented either as a map showing amounts of rainfall, or as a graph showing the relation between rainfall in the target area of a cloud seeding operation and rainfall in an adjacent unseeded area called a control area.

In general, the objective of commercial cloud seeding operations has been to increase the amount of precipitation over a given area above that which would naturally fall during the seeding period. Thus, the basic measurement for evaluation of the results is the amount of precipitation. The units of time studied vary from report to report. Some refer to storm periods of varying duration, but representing separable precipitation events; others refer to fixed periods of time, such as weeks, months, or years.

The measurement of precipitation is characterized either by the amounts at individual stations, by the averages of amounts at two or more stations, or by lines of equal depths of precipitation drawn on maps interpolating among stations. The

maps referred to are called isohyetal maps. A variation of the isohyetal map, often called an isopercentile map, shows the amounts of precipitation, not directly in inches of depth, but as percentages of normal or long-term average rainfall. This refinement is intended to account for the effects of geographic and topographic differences on precipitation patterns.

The evaluation reports using the isopercentile map usually impute to the effect of cloud seeding such regions of maximum percentage as occur within the areas chosen for seeding. It was generally inferred, in introductory discussions of the reports reviewed, that in the absence of seeding, the per cent of normal precipitation would not vary greatly over the areas involved. One difficulty with this approach is that in most storms there are rather wide variations among stations in the relative intensity of precipitation. As stated in the report of the Statistical Laboratory comprising Appendix C, "An analysis of isopercent of normal curves was performed for all storms during the year preceding the first year of seeding operations in the particular area and it was found that a wide variation of the per cent of normal precipitation is a most usual phenomenon." This being the case, the mere pointing out of regoins of maximum percentage of rainfall within a seeded area does not constitute proof that such concentrations would not have occurred naturally.

The isopercentile maps in the reports under review were usually presented together with accounts of the meteorological situations and the seeding patterns for the various storms. The maps sometimes show generator locations and arrows indicating

prevailing winds at effective elevations during the storms. The objection to these maps goes beyond that against the inference, mentioned in the previous paragraph, that in the absence of cloud seeding the maps would not show any appreciable variations in per cent of normal precipitation. The first further difficulty is that the times and locations of generator operations are only generally linked to the times and areas of the maxima. The second, and most serious difficulty is that there is no way to determine whether the maxima that did occur would not have occurred where and when they did in the absence of seeding.

In those evaluation reports where the precipitation for the seeded area is represented by recorded precipitation at one or more stations, the data are usually presented in one of two ways. In one method, the absolute range of precipitation values during cloud-seeding operations is compared with the range shown by records before seeding began. However, the length of time required to collect, under cloud-seeding conditions, a record which would be comparable with that for an unseeded period is too long to be feasible, considering the extreme natural variability in the amount of precipitation. The second method, designed to decrease the effects of this variability, is to compare the amounts of precipitation for the station or stations in the seeded target area with corresponding amounts in an unaffected area called the control area.

In one particular evaluation study reviewed, the ratio of total precipitation at an affected station during a two-month cloud-seeding period to the corresponding precipitation at a station outside the affected area, was compared to similar two-

month ratios for each of the entire 62 years of precipitation record prior to cloud seeding operations. It was found that the ratio during the seeded period was exceeded only twice during the 62 years and then in successive years in the 1890's. It should be noted that the authors of this evaluation study claimed only that the figures presented indicated that the precipitation pattern during the seeding period was unusual, giving increased confidence to the claim that seeding was responsible. This method of analysis, even though the figures thenselves may be impressive, is unsatisfactory as proof of the effectiveness of cloud seeding for several reasons. These objections, which will be illustrated by reference to this one particular evaluation report, are equally applicable to many other weather modification studies.

The first objection is to the use of a single station to represent the amount of precipitation occurring over a large area. This objection is difficult to resolve. In other studies reviewed, the frequent lack of adequate precipitation records often required that a choice be made between using a few long-period records or several shorter-period records. Studies made where a dense network of precipitation gages has been set up have indicated both that variation in the amount of precipitation over even small areas is considerable and that a dense observational network gives a more adequate picture of the precipitation pattern. Consequently, considerable study should be undertaken before a decision is made whether to use a small number of stations with long periods of record, or a larger number of short-term stations.

The second objection is that the relative importance of the amount by which the observed ratio exceeded the average was not presented. The third objection is that one month during which cloud seeding took place was excluded from the analysis. This omission was justified by the authors on the basis that the seeding during this month was claimed to have had an effect in the area in which the comparison or control station was located. Many similar instances of weather modification evaluation by means of arbitrarily selected data were noted in the reports reviewed. These selections, although generally made to take account of the actual experience of the operation, cast some doubts on the conclusions drawn, unless the physical facts supporting the selection are carefully presented. One way to avoid this difficulty would be to document in advance of the cloud seeding operations the area which it is intended to affect and the results proposed, and to decide, also in advance of the operations, which precipitation station or stations are to be used as target and control stations.

Certain more recent evaluation reports of weather modification operations have used orthodox statistical techniques. In these, the relationship between precipitation records for a station or group of stations within the target area and those for a supposedly unaffected control area is determined by plotting points representing amounts of precipitation during unseeded periods of record on a graph, and determining the line that best fits the points plotted. A mathematical method for determining the line of best fit is the method of least squares. This method produces, as a by-product, a measure of the significance of the

departure of any point or points from the line. This measure is then used to determine whether cloud seeding had an effect by demonstrating the probability that the departure of one or more points, representing seeded periods, from the line, could have occurred naturally.

The difficulties involved in the use of the foregoing method, as actually applied in the evaluation reports referred to, are pointed out by the Statistical Laboratory in Appendix C. Some of the difficulties are technical in nature, dealing with particular features of the least squares method as it has usually been employed. Other difficulties have to do with the fundamental assumptions basic to any regression method of analysis when applied to the problem of evaluating weather modification operations.

The technical difficulties stem from the fact that most evaluation reports have relied on the linear least squares method of regression analysis. Three assumptions basic to this method are of prime importance. One assumption is that the precipitation in the target is, on the average, a linear function of precipitation in the control area. It is reasonable to presume that in many cases a curvilinear relationship is more likely. The second assumption is that the distribution of observations of target rainfall about the average values indicated by the line of relationship follows a particular form termed by statisticians the "normal" distribution, or at times "the normal curve of error". These two assumptions regarding linearity and normality have seldom been checked by weather modification investigators. The violation of these assumptions, however, does not seem to be

as serious as the violation of the assumption of constant variance discussed in the following paragraph.

The third assumption is that, regardless of the amount of precipitation in the control area, the relative variability of amounts in the target area about the regression line remains constant. It is this last point that causes the greatest difficulty from a technical point of view. Whether one is dealing with storm precipitation totals or with monthly or seasonal amounts, the most obvious feature of any plotting is that as the amounts become larger the scatter increases, imparting a fan shape to the cloud of points. This circumstance leads to a possible misinterpretation of the significance of the deviation of a seeded point from the regression line. In the evaluation reports reviewed, a second line is usually drawn parallel to and above the regression line, beyond which the occurrence of any point is claimed to be significant. The point brought forth herein is that the line of significance should be set at an angle to the regression line rather than parallel, corresponding to the fan shape exhibited by the points. It is difficult to determine this diverging line of significance mathematically. A substitute technique has been developed by the Statistical Laboratory, in which the amounts of precipitation are expressed in terms such that the relative variability of the new target amounts from expectation will remain constant. It was found by trial that the square roots of storm precipitation amounts would exhibit a close approximation to this desired constancy.

A fundamental assumption basic to any statistical comparison to evaluate the effects of cloud seeding is either that

the control precipitation stations are not affected by the seeding program, or if they are affected, that the differences in effects between target and control stations are measurable. An instance has already been cited in which the belief was stated by an investigator that seeding had affected the control, giving this as the reason for the apparent lack of effect. A later instance states that the influence of cloud seeding activities over control precipitation stations, by an organization other than the one studied, could have been responsible for an apparent lack of effect during certain periods. If this influence is not recognized, a possible underestimate of the effect of seeding in the target area could result. It is a confusing circumstance that the same situation might produce an overestimate of the effect if the control precipitation stations were too close to generators, thus producing local overseeding and reduction of precipitation in their immediate vicinity, as is maintained to occur by some students of weather modification.

Finally, most investigators of weather modification who have relied on the regression method of analysis have assumed that the relationship between control and target precipitation amounts is stable. In other words, they have assumed that there is one simple average relationship which can be used as the basis for determining the effectiveness of a weather modification program. The Statistical Laboratory investigated this matter, and found that the relationship varies.

The evaluation reports which base their analysis upon monthly amounts of precipitation tacitly admit variations in the control-target relationship in presenting a separate analysis

for each calendar month. It is believed that such seasonal changes in the relationship as occur are based on meteorological and natural conditions causing differences in prevailing storm patterns in different periods of the year. There may also be seasonal variations in the relative numbers of storms exhibiting common patterns. These systematic differences intorduce an element of instability even into analyses based on annual amounts, since the numbers of storms of differing characteristics vary from year to year.

It is reasonable to expect that the intensity of storms in a given area would be affected in a systematic way by the topography and orientation of that area. Differential effects in two different areas would be due, among other things, to the fact that mountain barriers would probably not have the same orientation with respect to a storm for both areas, as well as to the fact that different storms would have intrinsically different intensity patterns. The consequences of ignoring the foregoing systematic differences are found in the wide variability of plotted points of precipitation from an assumed average line of relationship, in the fact that the distribution of departures from expected precipitation typically varies from that indicating a probability mechanism, and, to some extent also, in the phenomenon of increasing variability considered in the discussion of technical difficulties.

Evaluation Methods Employed in Current Investigation

As a result of critical analysis of other weather modification evaluation reports and independent studies by the

Statistical Laboratory, there was developed during the current investigation an objective method of evaluation which it is believed avoids most of the difficulties previously cited. The method was used in cloud seeding evaluation studies for three separate areas in California. The three particular areas studied were selected from the many projects in California because they presented the most favorable situations from the standpoint of selection of suitable control and target stations.

The areas were: the Carrizo Plain, an enclosed basin in the Coast Range, about 60 miles west of Bakersfield; the Southern Sierra area, encompassing portions of the watersheds of the Tule and Kern Rivers, and intervening drainage basins, in southeastern San Joaquin Valley; and Santa Barbara County, on the Pacific Coast.

In general, the method of evaluation involved the comparison of rainfall in the cloud seeding target area with simultaneous rainfall in another area assumed to be unaffected by the operation. The comparison was carried out separately for storms of several different meteorological classes. The relationships, by classes, between rainfall in the two areas were determined by plotting on a simple coordinate system the square roots of the amounts of precipitation for a large number of storms occurring during nonseeded years. The points representing the seeded storms were then superimposed on this diagram and compared with the nonseeded storms. A statistical test was made to determine whether the variation of the relationships observed in the seeded period from those in the nonseeded period was greater than might be expected. This analysis was also performed for

each of the several classes of storms. These ranged in general from a class of storm productive of relatively more rain in the target area than in the control area, to a class productive of relatively more rain in the control area than in the target area.

The program of segregating storms to account for the different relationships was assigned to a professional meteorologist. For the final evaluation studies, Mr. Edward M. Vernon, then Chief Regional Forecaster, United States Weather Bureau, San Francisco Municipal Airport, was called on to provide the meteorological basis for this segregation. His experience enabled him to propose a set of meteorological criteria which might characterize typical rainfall intensity patterns from different storm events.

The evaluation of weather modification operations in Santa Barbara County is presented hereinafter as an example of the technique developed during the current investigation. This study was a joint project of personnel of the Statistical Laboratory and of the Division of Water Resources, and covered programs of cloud seeding during the winter seasons of 1950-51, 1951-52, and half of the season of 1952-53. Details of similar studies, together with specific results, are given for the Carrizo Plain in Appendix C and for the Southern Sierra area in Appendix D.

Varying conditions of topography and orientation required the division of Santa Barbara County into six target areas, as shown on Plate 7, entitled "Santa Barbara County Cloud Seeding Evaluation Target and Control Areas", namely, Target 1, Upper Santa Ynez Basin; Target 2, Middle Santa Ynez Basin;

Target 3, Western Basins; Target 4, South Coast Basin; Target 5, Cuyama Valley; and Target 6, Sisquoc Basin.

Unfortunately, the Sisquoc Basin, consisting of approximately one-third of the total area of Santa Barbara County, contained no reliable precipitation stations. For that reason, this large area was necessarily excluded from the analysis.

In the other target areas, there were usable records of from one to three precipitation stations on which to base the analysis. These stations, together with reference numbers indicating their location on Plate 7, were as follows:

Target		Precipitation station	
Number	Name	Number	Name
1	Upper Santa Ynez Basin	1	Gibralter Dam
		2	Juncal Dam
		3	Los Prietos Ranger Station
2	Middle Santa Ynez Basin	4	Santa Ynez
3	Western Basins	5	Lompoc White Hills
		6	Los Alamos
		7	Santa Maria Weather Bureau Airport
4	South Coast Basin	8	San Marcos Pass
		9	Santa Barbara
		10	Santa Barbara CAA Airport
5	Cuyama Valley	11	Cuyama Post Office
		12	Cuyama Ranger Station
		13	Wasioja Forbes Ranch

According to the first contract between the commercial cloud seeding operator and the contracting local agencies in Santa Barbara County, the seeding in the winter of 1950-51 was designed to affect only the Upper Santa Ynez Basin. This seeding program was, therefore, distinguished from the subsequent

seasons, during which the entire county was considered to be the target area. Comparison of storm precipitation amounts in the targets for the two programs, however, indicated no significant difference in apparent effect connected with the two programs.

Three control precipitation stations were chosen on the coast north of Santa Barbara County, consisting of those at Lucia Willow Springs, Point Piedras Blancas, and San Luis Obispo Polytechnic, also indicated on Plate 7. An alternate control group, consisting of Paso Robles 4 NW, Lockwood, and Valleton, was used to check the validity of certain findings based on the first group.

Storms were separated and classified according to a modification of the system devised by Mr. Vernon for the Carrizo Plain study. The five storm classes finally chosen for the Carrizo Plain study, and outlined in Appendix F, were altered to correspond to the different orientation and topography of the Santa Barbara area. The changes and the reasoning leading to these changes are outlined in a supplement to Appendix F.

The values used in determining the regression lines were obtained by taking the square roots of the total amounts of precipitation for each storm. These amounts had been determined as sums of the storm precipitation amounts recorded at the representative precipitation stations, divided by the number of stations in each target. This transformation was undertaken to stabilize the conditional variance, that is, to reduce the tendency for the dispersion of points about the regression lines to increase with increasing amounts of precipitation.

Separate regression lines were computed for each of the four or five storm classes applicable to the particular target.

These regression lines were based on storms that occurred during the six years immediately preceding the beginning of cloud seeding, i.e., from January, 1945, to December, 1950. This early period is referred to subsequently as the historical period. It was found that, with a high degree of confidence, approaching certainty, these classes did differentiate the relationships between precipitation on the control and target areas. On the other hand, certain of the classes were found by a statistical test not to differ among themselves sufficiently to justify their separation as a basis for estimating expected amounts of rainfall. The classes giving similar predictions were grouped together to produce a final set of storm classes, as summarized in the second addendum to Appendix F.

The regressions for the storm classes finally chosen, based on storms of the period prior to seeding, are shown on Plate 8, entitled "Simultaneous 50 Per Cent Confidence Intervals for Storms of Specified Classes by Targets in Santa Barbara County". They are not shown as lines, however, since the lines obtained by the least squares method are only estimates, based on relatively small samples. The bands shown represent simultaneous 50 per cent confidence intervals for the various classes. In other words, the probability is one-half that, for the entire collection of bands, each and every true regression line is contained within its own band. The narrowness of the bands shows how well the data indicate the true regression lines.

The overlapping or separation of the bands illustrates the effectiveness of the classification system in differentiating the control-target relationships. The solid lines indicate the

portion of the band, for each class, which was based on actual precipitation data. Dashed lines indicate estimated extensions of the confidence bands. Examination of Plate 8 reveals that in no target is any band totally contained within another band. It was concluded from this separation that the classification systems finally used in the several targets did effectively differentiate control-target relationships.

An equally effective differentiation held true with respect to the other group of control stations, used as an alternate basis of comparison.

Plate 9, entitled "Comparison of Storms During Seeded Period With Historical Regressions, Santa Barbara County", compares precipitation from storms in the seeded periods with estimated regression lines, based on the period prior to seeding, for the various storm classes. A set of graphs has been drawn for each target area, consisting of a separate graph for each storm class, showing the estimated regression lines for the period prior to seeding, and symbols representing storms in the seeded periods. The values plotted are again square roots of mean storm precipitation in inches for the respective groups of stations, with control values on the X-axis and target values on the Y-axis. On this plate the regressions are shown as lines rather than bands, to simplify the presentation, since the bands have no significance with respect to the individual points. Circles represent storms during the winter of 1950-51, when the Upper Santa Ynez was the only target, and triangles represent storms occurring in the two following winter seasons, 1951-52 and part of 1952-53. Storms actually seeded are shown by solid symbols. Open symbols

represent unseeded storms during the seeding periods. Summer storms were excluded.

The generator logs of the commercial operator were examined in order to assign the cloud seeding operations to appropriate storms. The possibility that seeding operations meant to affect one storm might actually persist so as to influence a following storm was not considered in this study, nor were possible variations in seeding instructions to the operator aimed at producing differential effects in various parts of the county.

Comparison of the circles with the triangles on Plate 9 indicates no significant difference between the two seeding programs, as far as storm precipitation amounts in the target relative to amounts in the control are concerned. In comparing the graphs for the different storm classes visually, it may be noted that the intermediate storm classes, representing by far the greatest number of storms during the seeded periods, showed the most consistent excess of precipitation over the expected amounts.

A statistical test, called an "F test", was applied to answer the question, "Could the differences between the precipitation actually observed and that predicted on the basis of the regression analysis for the historical period be ascribed to chance alone?" The same question was asked twice, first concerning those storms actually seeded, and then concerning all storms during the contract period. The question was asked for each target and each storm class separately, since there always exists the possibility that the cloud seeding might be helpful in one situation and not in another. In every sub-target, significant values of "F" were found for the intermediate classes of storms of

Mr. Vernon's meridional-zonal classification, giving high degrees of confidence that the differences between seeded and historical periods were real. For the other classes of storms, there was no net increase. However, the small number of storms in these classes makes it improbable that any moderate change would be detected.

Table 2 indicates, both for storms actually seeded and for all storms in the seeding period, the probabilities, based on values of "F", that differences in regression obtained by chance would be smaller than those observed.

In interpreting this table, it is pointed out that a value of 1.00 would indicate that differences arising from chance would certainly be less than those observed. A value of 0.50 would indicate that about half the time the differences arising from chance variation would be less than those observed.

The larger this probability is, the more apt the experimenter is to decide that the observations "could not" be due to chance variation, and the more apt he is to decide they "must" be due to real differences. For any experimenter there is a value of this probability above which he is prepared to announce "a real difference exists". The larger this value, the less frequently he will announce chance differences as real. It is often quite difficult to decide what value is appropriate and what chance the experimenter is prepared to take. This involves a balancing of the costs of the operation and the consequences of announcing a fictitious seeding effect against the benefits to be obtained if seeding is effective.

For this study a value of 0.80 was chosen. As a result, in any test performed there were two chances in ten of

TABLE 2

PROBABILITY THAT STORMS OF SPECIFIED CLASSES DURING SEEDING PERIOD IN SANTA BARBARA COUNTY SHOWED REGRESSIONS WITH REAL DIFFERENCES FROM THOSE IN PERIOD PRIOR TO SEEDING

Sub-target	Storm class							Total
	Ia'	Ib'	Id'	Ie'-IIb	B	C	D	
Storms actually seeded								
1	ns	ns	--	--	0.99	ns	--	
2	--	ns	--	--	--	ns	0.999	
3	--	--	ns	0.999	--	ns	--	
4	ns	ns	--	--	0.97	ns	--	
5	ns	ns	--	--	0.99	ns	--	
Number of storms	11	8	4	37	22	12	33	53
All storms during seeding period								
1	ns	ns	--	--	0.94	ns	--	
2	--	ns	--	--	--	ns	0.99	
3	--	--	ns	0.999	--	ns	--	
4	ns	ns	--	--	0.91	ns	--	
5	ns	ns	--	--	0.98	ns	--	
Number of storms	19	15	11	64	41	23	60	98

ns Not significant; probability of difference is less than 0.80, too low to justify statement that difference is real.

-- Storm class not represented in this sub-target.

announcing a positive result when actually there was no seeding effect. In fact, even if the true effect is sizeably negative there is a good chance of announcing a positive result. This low value of 0.80 was chosen to ensure that any positive seeding effect had a reasonable chance of showing up in the analysis.

In order to give a measure to the effect of the cloud seeding program on the rainfall in the several target areas, the recorded rainfall amounts for the seeded storms were compared with the expected amounts and were retransformed to inches of excess or deficiency of precipitation from the expected amounts. Table 3 shows the amounts of excess precipitation in inches.

The expression of the precipitation excesses in units of inches per station is intended to account for the different number of stations in each target, and thus provide a measure of comparability among the targets. These values should not be interpreted as actual averages for the targets.

Discussion of Results of Evaluation Studies

The results of the evaluation studies for the three areas, Carrizo Plain, Southern Sierra, the details of which may be found in Appendixes C and D, and Santa Barbara County, are summarized in Table 4, with the various storm classes condolidated for purposes of illustration into the three general classes, meridional storms, intermediate storms, and zonal storms.

Table 4 indicates that in the Carrizo Plain cloud seeding produced different effects in each of the two years in which seeding took place, that in the Southern Sierra area the storms were not significantly affected by cloud seeding, and that in

TABLE 3

WAS SEEDING EFFECTIVE IN SANTA BARBARA
DECEMBER, 1950 TO MAY, 1951, NOVEMBER, 1951 TO MAY, 1952;
NOVEMBER-DECEMBER, 1952

Storms actually seeded						All storms during seeding period					
Sub-target	Storm class	Number of storms in program	Probability of excess	Total precipitation excess, in inches per station	Per cent of excess over expectation	Sub-target	Storm class	Number of storms in program	Probability of excess	Total precipitation excess, in inches per station	Per cent of excess over expectation
1	Ia'	11	ns	-0.14	--	1	Ia'	19	ns	-0.66	--
	Ib'	8	ns	4.62	--		Ib'	15	ns	3.77	--
	B	22	0.99	8.46	64		B	41	0.94	18.02	76
	C	12	ns	-0.80	--		C	23	ns	-2.56	--
2	Ib'	8	ns	2.51	--	2	Ib'	15	ns	2.80	--
	C	12	ns	0.24	--		C	23	ns	-0.59	--
	D	33	0.999	7.80	95		D	60	0.99	9.49	67
3	Id'	4	ns	0.30	--	3	Id'	11	ns	-0.30	--
	Ie'-IIb	37	0.999	8.01	70		Ie'-IIb	64	0.999	9.60	51
	C	12	ns	0.60	--		C	23	ns	0.30	--
4	Ia'	11	ns	0.26	--	4	Ia'	19	ns	-0.40	--
	Ib'	8	ns	2.48	--		Ib'	15	ns	2.82	--
	B	22	0.97	5.82	49		B	41	0.91	10.52	50
	C	12	ns	0.91	--		C	23	ns	-0.28	--
5	Ia'	11	ns	0.19	--	5	Ia'	19	ns	-0.03	--
	Ib'	8	ns	1.75	--		Ib'	15	ns	1.70	--
	B	22	0.99	3.34	79		B	41	0.98	5.51	73
	C	12	ns	-0.08	--		C	23	ns	-0.85	--

ns - Not significant at 0.80 level.

TABLE 4

PROBABILITY THAT RELATION OF TARGET PRECIPITATION VALUES TO CONTROL VALUES FOR SEEDED STORMS WAS ACTUALLY DIFFERENT FROM THAT FOR HISTORICAL UNSEEDED YEARS

Area	Meridional storms	Intermediate storms	Zonal storms
Carrizo Plain			
1950-51, 29 storms	0.92	0.98 (negative)	ns
1951-52, 33 storms	ns	ns	0.94 (negative)
1950-52, 62 storms	ns	ns	0.95 (negative)
Southern Sierra Project			
24 storms	ns	ns	ns
Santa Barbara County			
53 storms			
Target 1	ns	0.99	ns
2	ns	0.999	ns
3	ns	0.999	ns
4	ns	0.97	ns
5	ns	0.99	ns

ns - Not significant at 0.80 level.

Santa Barbara County there were significant increases in rainfall from the intermediate storms as a result of cloud seeding. One would infer from these results that the precipitation from certain storms was increased and that the precipitation from others was decreased due to cloud seeding. If this is the case, it follows that professional cloud seeders should exercise caution in the selection of storms to seed.

In evaluation studies for the three foregoing projects no mention was made of the methods and techniques of operation which were employed, and no consideration was given to these factors in the evaluation studies. In both the Carrizo Plain and the Southern Sierra Projects the cloud seeding was done by airplane using silver iodide and sulphur trioxide. Ground generators with silver iodide were used in the Santa Barbara County

Project. The differing results of the evaluation studies might be taken to indicate that ground generators are more successful than cloud seeding from airplanes. However, it is considered that the limited number of studies do not establish such a conclusion, and it is possible that the apparent differences in the success of seeding are due to the frequency of undiscovered subclasses of storms.

On the basis of data presented in Table 4 it would appear strongly probable that weather in California has been modified by cloud seeding operations. It can be stated that there is no reasonable doubt that the precipitation relationships in seeded storms were significantly different from those in the nonseeded storms. However, it is not possible to state without qualification that the cloud seeding operations produced the differences. It is possible that Mr. Vernon's storm categories could be further divided, with some subclasses favoring the targets, and others the controls. A change may have taken place in the frequency of storms of these subclasses between the unseeded period and the seeded period. This could have resulted, in the case of the Santa Barbara Project, in a natural favoring of the targets during the seeded period, and in the case of the Carrizo Plain Project, in an unfavorable effect. There are some indications that this may actually have happened in the Santa Barbara Project, since in every target, the precipitation excess for all intermediate class storms in the seeding period was greater than that for the storms actually seeded, in two targets representing a greater percentage excess than that for the storms actually seeded. Therefore, the differences exhibited may have been due

not to the effects of seeding, but to meteorological principles of storm segregation not included in the storm classification system used.

The last statements lead to the fact that none of the evidence produced to the present time on the effects of actual cloud seeding operations constitutes documentary evidence. The documentation referred to would consist of data which would enable one to separate clearly the influences responsible for variations in target-control relationships, or at least to calculate the probabilities attaching to different possible influences.

The Statistical Laboratory has suggested a procedure for solving the foregoing difficulty and providing documentary evidence of the effects of a program of cloud seeding. This procedure would consist of prearranging a schedule of cloud seeding operations under which roughly half of the seeding opportunities would be accepted and seeded, while the others would be left unseeded, in accordance with the dictates of a chance mechanism such as flipping a coin, or preferably, by use of a table of random numbers. It would be necessary to keep strictly to the schedule dictated by chance for a considerable length of time. The time should be sufficient to provide a sizeable number of storms, both seeded and unseeded, for which the amounts of precipitation would be compared and subjected to statistical tests. These tests in turn would be able to measure very accurately the probability that seeding was effective. Commercial weather modification operations could be adapted to these procedures. Cooperation among several projects in carrying out a

program could produce the indication of effectiveness for all in a shorter time than would be required to give an answer with equal assurance for one concern alone. The suggested procedure is discussed at length in Appendix C.

Referring again to Table 4, it is clear that there were important differences in the target-control relationships associated with certain cloud seeding operations. These differences were of such magnitude that it is important from the standpoint of water resources development to determine the extent to which cloud seeding is the active agent. It has been demonstrated that further consideration of past operations would not be profitable, since the required data is not available. Thus, attention should be given to future operations. Encouragement and support should be given to objective investigations of these future operations. Some of these investigations should involve specifying in advance the conditions of the operations, in the manner indicated in the previous paragraph.

CHAPTER IV. SUMMARY OF CONCLUSIONS, AND RECOMMENDATIONS

As a result of the studies of weather modification conducted in connection with the current investigation, the following conclusions and recommendations are set forth.

Summary of Conclusions

1. There is evidence that the physical mechanism exists whereby it is possible to modify the amount and pattern of precipitation from a given storm event. However, the conditions under which this mechanism operates are exceedingly complex, so that it has yet to be determined whether anyone has developed the ability to exercise effective control of rainfall amounts over desired areas.

2. The kinds of evaluations and evidence as to the effects of weather modification which have been presented heretofore are so varied and so circumstantial that it is not possible to accept the findings as conclusive.

3. In connection with the current investigation, the evidence that has been analyzed with conscientious effort to maintain strict objectivity indicates the weather in California has been modified. Although it is not possible to credit without reservation the rainmaking operations with the differences in precipitation which were observed, there is no reasonable doubt that the amounts of precipitation from seeded storms were different from those expected on the basis of unseeded storms. In one of the projects analyzed, an increase of 95 per cent over expectation for a class of 33 storms was noted.

4. The evidence indicates that, often independent of the intentions of the operators, some categories of storm events have been modified to increase the resulting precipitation, others have not been affected, while still others have been so changed from their natural condition that less precipitation fell than would have fallen without the operation. Unfortunately, the definition of these storm categories is only tentative. When this definition has been sufficiently refined, it may be possible to demonstrate the operation of the mechanism giving rise to such paradoxical results.

5. Conclusive demonstration of the effectiveness of a given program for artificial modification of precipitation is not possible on the basis of available data on past operations. The natural variability of precipitation precludes such a determination. However, application to future operations of the principle of a randomized experiment can give an indication of effectiveness with a considerable degree of assurance.

Recommendations

1. That encouragement and assistance be given to public and private agencies and persons concerned with artificial modification of precipitation in order to establish and maintain adequate systems for the collection of basic data necessary for evaluation, particularly records of precipitation.

2. That agencies contracting for weather modification services be encouraged to include specific performance requirements in their contracts, and to consider as one measure of performance the results of randomized acceptance of seeding opportunities.

3. That in view of the significant findings of the current investigation, additional investigation be undertaken to establish the extent to which weather modification operations may be relied upon to furnish a new resource of water. The investigation should include the conduct of randomized weather modification operations along lines suggested in Appendix C of this bulletin.

APPENDIX A

LAWS PERTAINING TO WEATHER MODIFICATION ENACTED BY 1951 CALIFORNIA LEGISLATURE

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CHAPTER 1374, STATUTES OF 1951

An act to amend Section 9 of the Riverside County Flood Control and Water Conservation District Act, relating to the powers of the Riverside County Flood Control and Water Conservation District.

(Approved by Governor July 7, 1951. Filed with Secretary of State July 9, 1951.)

The people of the State of California do enact as follows:

Section 1. Section 9 of the Riverside County Flood Control and Water Conservation District Act is amended to read:

Sec. 9. The objects and purposes of this act are to provide for the control of the flood and storm waters of said district and the flood and storm waters of streams that have their source outside of said district, but which streams and the said waters thereof flow into said district, and to conserve such waters for beneficial and useful purposes by retarding, spreading, storing, retaining and causing to percolate into the soil within said district, or without said district, such waters, or to save or conserve in any manner all or any of such waters and protect from such flood or storm waters, the watercourses, watersheds, public highways, life and property in said district, and to prevent waste of water or diminution of the water supply in, or unlawful exportation of water from said district, and to obtain, retain and reclaim drainage, storm, flood and other waters for beneficial use in said district.

Riverside County Flood Control and Water Conservation District is hereby declared to be a body corporate and politic and as such shall have power:

1. To have perpetual succession.

2. To adopt a seal and alter it at pleasure.

3. To sue and be sued in the name of said district in all actions and proceedings in all courts and tribunals of competent jurisdiction.

4. To acquire, by purchase, lease, construction or otherwise, or contract to acquire, lands, rights of way, easements, privileges and property of any kind, whether real, personal or mixed, and to construct, maintain and operate any and all works or improvements within or without the district necessary, convenient or proper to carry out any of the objects or purposes of this act, and to complete, extend, add to, repair or otherwise improve any works or improvements or property acquired by it as authorized by this act; to indemnify or compensate any owner of land or other property for any injury or damage caused by the exercise of the powers conferred by this act.

5. To take by grant, purchase, gift, devise or lease, or otherwise, and to hold, use, enjoy and to lease or dispose of real, personal or mixed property of every kind within or without the district necessary or convenient to the full exercise of its powers.

6. To incur indebtedness, and to issue bonds in the manner herein provided.

7. To store water in surface or underground reservoirs within or outside of the district for the common benefit of the district or a zone or zones thereof; to conserve and reclaim water for present and future use within the district; to appropriate and acquire water and water rights, and import water into the district and to conserve within or outside the district, same for any useful purpose to the district; to commence, maintain, intervene in and compromise, in the name of the district, or otherwise, and to assume the costs and expenses of any action or proceeding involving or affecting the ownership or use of water or water rights within the district used or useful for any purpose of the district or of common benefit to any land situated therein, or involving the wasteful use of water therein; to commence, maintain, intervene in, defend and compromise and to assume the cost and expenses of any and all actions and proceedings hereafter begun; to prevent contamination, pollution or otherwise rendering unfit for beneficial use the surface or subsurface water used in said district, and to commence, maintain and defend actions and proceedings to prevent any such interference with the aforesaid waters as may endanger or damage the inhabitants, lands, or use of water in the district; provided, however, that the said district shall not have the power to intervene or take part in, or to pay the costs or expenses of actions or controversies between the owners of lands or water rights within the boundaries of the district and which do not involve taking water outside or away from the district.

8. To control the flood and storm waters of said district and the flood and storm waters of streams that have their source outside of said district, but which streams and the flood waters thereof, flow into said district, and to conserve such waters for beneficial and useful purposes within said district by retarding, spreading, storing, retaining and causing to percolate into the soil within or without said district, or to save and conserve in any manner all or any of such waters and protect from damage from such flood or storm waters the watercourses, watersheds, public highways, life and property in said district provided that water rights now existing be not thereby infringed upon.

9. To have and exercise the right of eminent domain, either within or without said district, and in the manner provided by law for the condemnation of private property for public use, to take any property necessary to carry out any of the objects or purposes of this act, whether such property be already devoted

to the same use by any district or other public corporation or agency or otherwise, and to condemn, any existing works or improvements in said district now or hereafter used to control flood or storm waters or to conserve such flood or storm waters or to protect any property in said district from damage from such flood or storm waters, and it is hereby declared that the use of the property, lands, rights of way, easements, or materials which may be condemned, taken or appropriated under the provisions of this act, is a public use subject to the regulation and control of the State in the manner prescribed by law; provided, however, that nothing in this act contained shall be deemed to authorize said district, or any person or persons to divert the waters of any river, creek, stream, irrigation system, canal or ditch, from its channel, to the injury or detriment of any person, or persons, having any interest in such river, creek, stream, irrigation system, canal or ditch, or the waters thereof or therein, unless compensation be first ascertained and paid therefor, under the laws of this State authorizing the taking of private property for public use; and provided further, that no right shall exist in behalf of said district to take by condemnation any property, including water rights, that is now devoted to beneficial use in Orange County; nor to take by condemnation any water rights or property necessary for exercising said water rights that are now devoted to beneficial use, or are now in the process of being devoted to beneficial use in Orange County, within an area along and adjacent to the trunk channel of the Santa Ana River extending from the easterly boundary of Orange County to the Jurupa Narrows and lying between the bluffs on either side of said river, but excluding therefrom any part of the Corona underground water basin as said basin is defined in that certain action in the Superior Court of the State of California, in and for the County of Riverside, numbered 22046, and entitled the Corona Foothill Lemon Company, a corporation, et al. vs. Charles E. Lillibridge, et al.

The power of eminent domain vested in the board of supervisors of said district shall include the power to condemn in the name of the district with the fee simple or any lesser estate or interest in any real property which said board by resolution shall determine is necessary for carrying out the purposes of this act. Such resolution shall be prima facie evidence that the taking of the fee simple or any lesser estate or interest in such property, as the case may be, is necessary. Whenever real property which is devoted to or held for some other public or quasi-public use is required by the district for flood control or water conservation purposes, the district may condemn real property adjacent thereto or in the immediate vicinity thereof to be exchanged for the real property required by the district as aforesaid for flood control or water conservation purposes.

10. To enter upon any land, to make surveys and locate the necessary works of improvement and the lines of channels, conduits, canals, pipelines, roadways and other rights of way; to acquire by purchase, lease, contract condemnation, gift or other

legal means all lands and water and water rights and other property necessary or convenient for the construction, use, supply, maintenance, repair and improvement of said works, whether in this or in another state, including works constructed and being constructed by private owners, lands for reservoirs, for storage of necessary water, and all necessary appurtenances, and also where necessary or convenient to said end, and for said purposes and uses, to acquire and hold the stock of corporations, domestic or foreign, owning water or water rights, canals, water works, power plants, franchises, concessions or rights; to enter into and to do any and all acts necessary or proper for the performance of any agreement with the United States, or any state, county, district of any kind, public or private corporation, association, firm or individual, or any number of them, for the joint acquisition, construction, leasing, ownership, disposition, use, management, maintenance, repair or operation of any rights, works or other property of a kind which might be lawfully acquired or owned by said Riverside County Flood Control and Water Conservation District; to acquire the right to store water in any reservoirs, or to carry water through any canal, ditch or conduit not owned or controlled by the district; to grant any owner or lessee the right to the use of any water or the right to store such water in any reservoir of the district or to carry such water through any tunnels, canal, ditch or conduit of the district; to enter into and to do any acts necessary or proper for the performance of any agreement with any district of any kind, public or private corporation, association, firm or individual, or any number of them for the transfer or delivery to any such district, corporation, association, firm or individual of any water right or water pumped, stored, appropriated or otherwise acquired, or secured for the use of the Riverside County Flood Control and Water Conservation District, or for the purpose of exchanging the same for other water, water right or water supply to be delivered to said district by the other party to said agreement; to cooperate with, and to act in conjunction with the State of California, or any of its engineers, officers, boards, commissions, departments or agencies, or with the Government of the United States, or any of its engineers, officers, boards, commissions, departments or agencies, or with any public or private corporation, in the construction of any work for the controlling of flood or storm waters of said district, or for the protection of life or property therein, or for the purpose of conserving said waters for beneficial use within said district, or in any such works, acts, or purposes provided for herein, and to adopt and carry out any definite plan or system of work for any such purpose as authorized herein.

11. To cause taxes and assessments to be levied and collected for the purpose of paying any obligation of the district and to carry out any of the purposes of this act, in the manner hereinafter provided.

12. To carry on technical and other investigations of all kinds, make measurements, collect data and make analyses, studies, and inspections pertaining to water supply, water rights, control of floods and use of water, both within and without said district, and for such purposes said district shall have the right of access through its authorized representatives to all properties within said district.

13. To carry on a program of artificial nucleation for the purpose of increasing and controlling rainfall within, or in the immediate vicinity of, any watershed located wholly or partially within the district.

The total amount of taxes levied for the purpose of carrying on any program under this subdivision shall not be in excess of five cents ($0.05) for each one hundred dollars ($100) of assessed valuation of the taxable property within the district.

The authority of the district to carry on any program under this subdivision shall terminate on October 1, 1953.

14. To make contracts and to employ labor and to do all acts necessary for the full exercise of all powers vested in said district, or any of the officers thereof by this act.

CHAPTER 1596, STATUTES OF 1951

An act to add Section 17.1 to the State Water Resources Act of 1945, authorizing the State Water Resources Board to contract with public and private organizations and persons for research work relative to the production and control of rainfall by artificial means, and making an appropriation therefor.

(Approved by Governor July 18, 1951, Filed with Secretary of State July 18, 1951.)

The people of the State of California do enact as follows:

Section 1. Section 17.1 is added to the State Water Resources Act of 1945, to read:

Sec. 17.1. The Water Resources Board is authorized to contract with public and private organizations and persons for research relative to the production and control of rainfall by artificial means.

Sec. 2. There is hereby appropriated to the State Water Resources Board out of the General Fund in the State Treasury fifty thousand dollars ($50,000) to be expended in research in the production and control of rainfall by artificial means.

CHAPTER 1677, STATUTES OF 1951

An act to provide for the regulation and licensing of interference or attempts to interfere by artificial means with natural condensation and precipitation of rain, snow, moisture or water in any form contained in the atmosphere; to provide for the enforcement of said act and penalties for the violation thereof.

(Approved by Governor July 23, 1951. Filed with Secretary of State July 24, 1951.)

The people of the State of California do enact as follows:

Section 1. The public interest, health, safety, welfare and necessity require that scientific experimentation in the field of artificial nucleation, and that scientific efforts to develop, increase and regulate natural precipitation be encouraged, and that means be provided for the regulation and control of interference by artificial means with natural precipitation of rain, snow, moisture or water in any form contained in the atmosphere, within the State of California, in order to develop, conserve and protect the natural water resources of this State and to safeguard life and property.

Sec. 2. Unless the context otherwise requires, the following definitions shall govern the construction of this act:

(a) "Department" means the Department of Public Works acting through the State Engineer.

(b) "Person" means any person, firm, association, organization, partnership, company, corporation, private or public, county, city, city and county, district, or other public agency.

(c) The singular number includes the plural and the plural, the singular.

(d) The masculine gender includes the feminine and the neuter.

(e) "Shall" is mandatory and "may" is permissive.

(f) The present tense includes past and future tenses, and the future, the present.

Sec. 3. No person, without first securing a license from the department, shall cause or attempt to cause condensation or precipitation of rain, snow, moisture or water in any form contained in the atmosphere, or shall prevent or attempt to prevent by artificial means the natural condensation or precipitation of rain, snow, moisture or water in any form contained in the atmosphere.

Sec. 4. Any person desiring to do any of the acts specified in Section 3 of this act may file with the department an application in writing for a license. Each application shall be accompanied by a filing fee fixed by the department with the approval of the Department of Finance but not to exceed fifty dollars ($50) and shall be on a form to be supplied for such purpose by the department.

Sec. 5. Every application shall set forth all of the following:

(a) The name and post-office address of the applicant.

(b) The previous education, experience and qualifications of the applicant, or, if the applicant is other than an individual, the previous education, experience and qualifications of the persons who will be in control of and charged with the operations of the applicant.

(c) A general description of the operations which the applicant intends to conduct and the method and type of equipment that the applicant proposes to use.

(d) Such other pertinent information as the department may require.

Sec. 6. Upon the filing of the application upon a form supplied by the department and containing the information prescribed by this act and accompanied by the required filing fee the department shall issue a license to the applicant entitling the applicant to conduct the operations described in the application for the calendar year for which the license is issued, unless the license is sooner revoked or suspended. Such license may be renewed annually upon application to the department, accompanied by a renewal fee fixed by the department with the approval of the Department of Finance but not to exceed twenty-five dollars ($25), on or before the last day of January of the calendar year for which the license is renewed.

Sec. 7. Prior to undertaking any operation authorized by the license the licensee shall file with the department and cause to be published a notice of intention. The licensee shall then confine his activities for that operation substantially within the time and area limits set forth in the notice of intention.

Sec. 8. The notice of intention shall set forth all of the following:

(a) The name and address of the licensee.

(b) The nature and object of the intended operation and the person or persons on whose behalf it is to be conducted.

(c) The area in which and the approximate time during which the operation will be conducted.

(d) The area which will be affected by the operation as near as the same may be determined in advance.

Sec. 9. The applicant shall cause the notice of intention to be published at least once a week for three consecutive weeks in a newspaper having a general circulation and published within any county wherein the operation is to be conducted and in which the affected area is located, or, if the operation is to be conducted in more than one county or if the affected area is located in more than one county or is located in a county other than the one in which the operation is to be conducted, then such notice shall be caused to be published in like manner in a newspaper having a general circulation and published within each of such counties. In case there is no newspaper published within the appropriate county publication shall be made in a newspaper having a general circulation within the county.

Sec. 10. Proof of publication shall be filed by the licensee with the department within 15 days from the date of the last publication of the notice. Proof of publication shall be by copy of the notice as published attached to and made a part of the affidavit of the publisher or foreman of the newspaper publishing the notice.

Sec. 11. Every licensee shall keep and maintain a record of all operations conducted by him pursuant to his license showing the method employed, the type of equipment used, the times and places of operation of the equipment, the name and post-office address of each person participating or assisting in the operation other than the licensee and such other information as may be required by the department and shall report the same to the department immediately upon the completion of each operation. Each licensee shall further prepare and maintain an evaluation statement for each operation which shall include a report as to estimated precipitation, defining the gain or loss occurring from nucleation activities, together with supporting data therefor. This statement, together with such other pertinent information as the department may require, shall be sent to the department upon request by the department.

Sec. 12. Notwithstanding any provision of this act to the contrary, the department may grant a licensee permission to undertake an emergency nucleation project, without compliance by the licensee with the provisions of Sections 7 to 10, inclusive, of this act, if the same appears to the department to be necessary or desirable in aid of extinguishment of fires.

Sec. 13. Any license may be revoked or suspended if the department finds, after due notice to the licensee and a hearing thereon, that the licensee has failed or refused to comply with any of the provisions of this act. The proceedings herein referred to shall be conducted in accordance with the provisions of the Administrative Procedure Act, Chapter 5, Part 1, Division 3, Title 2 of the Government Code and the department shall have all the powers granted therein.

Sec. 14. Any person who violates any provision of this act is guilty of a misdemeanor.

APPENDIX B

BIBLIOGRAPHY OF PUBLISHED REPORTS ON CLOUD PHYSICS AND WEATHER MODIFICATION

Fairly comprehensive bibliographies of reports on cloud physics and weather modification may be found in "Meteorological Abstracts and Bibliography", published by the American Meteorological Society, Boston, Massachusetts, with Vol. 1, No. 3, March, 1950, particularly devoted to this subject, and in the December, 1952, issue of the "Transactions" of the American Geophysical Union. The bibliography in the Transactions is incorporated in an article by Mr. Ferguson Hall, entitled "Status of Possibilities of Artificial Precipitation".

A bibliography of papers and reports on the subject of ice-crystal nuclei and sublimation particles is appended to Appendix G of this bulletin.

Other published reports which have come to attention during the current investigation are listed in the following bibliography, which is believed to be essentially complete as of September, 1953.

BIBLIOGRAPHY OF PUBLISHED REPORTS ON
CLOUD PHYSICS AND WEATHER MODIFICATION

Aliverti, G., and G. Lovera, Sui nuclei di condensazione di origine marittima, Geofisica e Meteorologia, v.1, no. 23, pp. 33-35, 1953.

American Institute of Aerological Research, Analysis of cloud seeding potentialities in Santa Clara County, Report No. 46, January 24, 1951.

---. Analysis of cloud seeding potentialities in Southern California, Report No. 81, October 26, 1951.

American Meteorological Society, Meteorological Abstracts and Bibliography, Volume 1, No. 3. March, 1950.

Anonymous, Eine neue Methode zur künstlichen Erzeugungen von Niederschlag aus Cumuluswolken, Annalen der Meteorologie, Hamburg, v. 5, no. 1-2, pp. 45-46, 1952.

Barnes, C. S., Precipitation control, Proceedings, Western Snow Conference, Boulder City, Nevada, pp. 70-72, 1 pl., April, 1950.

Barton, M., Analysis of attempts to increase snowfall and resultant runoff by winter cloud-seeding in Southern Oregon Cascade Mountains, 1951-52; 1952-53.

First progress report, August 20, 1952; Second progress report, September, 1953 (Unpublished).
Oregon Agricultural Experiment Station, Medford Branch, and Oregon Agricultural Research Foundation, Corvallis, Ore.

Battle, J. A., Report of cloud-seeding operations in The Santa Ana River Watershed and Escondido Drainage Area, November 1, 1950 through April 15, 1951, Santa Ana River Weather Corporation, 1951.

Battle, J. A., W. F. Jones, and C. J. Todd, Report of cloud-seeding experiments for The Grand River Weather Improvement Assn., May 15 - July 31, 1952, Weather Modification Company, 21 pp., October 6, 1952.

---., Report of cloud-seeding experiments in the San Diego County and the Santa Ana River Watershed, November 1, 1951 through April 15, 1952 (Revised Edition), San Diego County Weather Corporation and Santa Ana River Weather Corporation, 141 pp., June 10, 1952; Supplement, 7 pp., October 1, 1952.

---., Report of cloud-seeding experiments in Santa Clara County, December 1, 1951 through March 31, 1952, Weather Modification Company, 59 pp., July 7, 1952.

Beaumont, R. T., Analysis of attempts to increase precipitation by cloud-seeding at Medford, Oregon, November, 1949, to April, 1950, and November, 1950, to April, 1951, Oregon Agricultural Experiment Station, Medford Branch, and Oregon Agricultural Research Foundation, Corvallis, Oregon, 1951 (Unpublished).

---., Cloud seeding Analysis in Oregon,
Oregon Agricultural Experiment Station, Medford, Ore., Technical Paper No. 753, 6 pp., 1953.
Reprint, Bulletin of the American Meteorelogical Society, v. 34, no. 7 pp. 298-303, September, 1953.

Blanchard, D. C., The behavior of water drops at terminal velocity in air, Transactions, of the American Geophysical Union, v. 31, no. 6, pp. 836-842, December, 1950.

Bollay, E., and R. D. Elliott, Preliminary report on cloud seeding operations for the City of San Diego during February, March, and April, 1951, North American Weather Consultants, 6 pp., May, 1951 (Unpublished).

---., Final report on cloud seeding operations in the San Diego area, February to April, 1951,
North American Weather Consultants, Report No. 6-1, 24 pp., July, 1951.

---., Report on cloud seeding operations in the upper Santa Ynez drainage basin during the period December, 1950, through April, 1951,
North American Weather Consultants, Report No. 6-3, 21 pp., July, 1951.

---., Report on the cloud-seeding operations in the Tillamook Burn during the period August, 1951 - October 2, 1951.

---., Report on Cloud seeding operations in the Coeur d'Alene Lake watershed, during the period August, 1951 - November, 1951.

---., Report on cloud seeding operations in the Upper San Joaquin Basin, during the period January, 1951 - April, 1952.

---., Report on cloud seeding operations in the Southern Cascades, during the period November, 1951 - April, 1952.

---., Report on cloud seeding operations in Santa Barbara County, during the period November, 1951 - May, 1952.

---., Cloud seeding potentialities in Los Angeles County, October, 1952.

---., Report on cloud seeding operations in the Coeur d'Alene Lake watershed, during the period September, 1952 - February, 1953.

---., Report on cloud seeding activities in the Southern Cascades, during the period November, 1952 - April, 1953.

---., Report on cloud seeding operations in the Central Sierras, during the period March, 1953 - May, 1953.

----., Report on cloud seeding operation in Custer County, Montana, during the period May, 1953 - July, 1953.

---., Report on cloud seeding operations in the upper San Joaquin Basin, during the period October, 1952 - September, 1953.

Bowen, E. G., Australian experiments in artificial rainmaking, Summary of talk presented at Weather Bureau seminar, Washington, D.C., Nov. 7, 1951, Bulletin of the American Meteorological Society, v. 33, no. 6, pp. 244-246, June, 1952.

---., Australian experiments on artificial stimulation of precipitation, Weather, v. 7, pp. 204-209, July, 1952.

---., Radar observations of rain and their relation to mechanisms of rain formation, Journal of Atmospheric and Terrestrial Physics, v. 1, no. 3, pp. 125-140, 1950.

Bowen, E. G. and K. A. Davidson, A raindrop spectrograph, Quarterly Journal of the Royal Meteorological Society, v. 77, no. 333, pp. 445-449, July, 1951.

Cooper, B. F., A balloon-borne instrument for Telemetering raindrop-size distribution and rainwater content of cloud, Australian Journal of Applied Science, v. 2, no. 1, pp. 43-55, 1951.

Cundiff, S. A., An industrial operation to produce precipitation, Proceedings, Western Snow Conference, Boulder City, Nevada, pp. 29-34, April 1950.

Das, P. K., The growth of cloud droplets by coalescence, Indian Journal of Meteorology and Geophysics, v. 1, no. 2, pp. 137-144, 1950.

Day, G. A., Radar observations of rain at Sydney, New South Wales, Australian Journal of Applied Science, v. 6, no. 2, pp. 229-239, 1953.

Dessens, H., The microstructure and artificial precipitation of a supercooled fog (in French), Compte-rendue hebdomadaire des seances de l'Academiie des Sciences, Paris, C.-R. Acad. Sci., Paris, v. 235, pp. 1675-1678, 1952.

---., Some remarks on the study of the microphysics of natural clouds, Centennial Proceedings of the Royal Meteorological Society, pp. 59-60, 1950.

---., The use of spiders' threads in the study of condensation nuclei, Quarterly Journal of the Royal Meteorological Society, v. 75 pp. 23-27, 1949.

Dessens, H., C. LaFargue, and P. Stahl, New work on condensation neuclei (in French) Annales de Geophysique, v. 8, no. 1, pp. 21-32, 1952.

Dobson, G. M. B., Ice in the atmosphere, Quarterly Journal of the Royal Meteorological Society, v. 75, pp. 117-130, 1949.

---., Physics of clouds and precipitation, Centennial Proceedings of the Royal Meteorological Society, pp. 34-36, 1950.

Dorsch, R. G., and P. T. Thacker, Photomicrographic investigation of spontaneous freezing temperatures of supercooled water droplets, National Advisory Council for Aeronautics, Technical Note 2142, July, 1950.

Dufour, L., Peut-on faire pleuvoir artificiellement? Institut Royal Meteorologique de Beligique, Publications, series B, no. 4, 15 pp., 1952.

---., Termperatures de coexistence de cristeaux de glace et de gouttes salées dans l'atmosphére,
Institut Royal Météorologique de Belgique, Publications, series B, no. 5, 19 pp., 1952.

Elliott, R. D., Increasing precipitation through cloud seeding, Weatherwise, v. 4, no. 4, pp. 88-90, August, 1951.

---., Methods of evaluation in cloud seeding, Proceedings of the 20th Annual Western Snow Conference, (1952).

---., The economic value of systematic cloud seeding, Proceedings of the 14th Annual Pacific Northwest Conference on Banking, 1953.

Gardner, C., Jr., Rainmaking and South Dakota's need for water, South Dakota Natural Resources Commission, Resources Bulletin, File Abstract, v. IV, no. 1-A, 8 pp., January 2, 1951; Supplement by D. F. Pearson, 13 pp., January 1, 1952.

Georgii, W., Teoriá del cambio de fases del agua y su applación en el problema de la lluvia artificial, Annales de la Sociedad Cientifica, Argentina, v. 148, pp. 343-364, 1949.

Grant, L. O., Meteorological investigations on the effects of seeding clouds for increasing precipitation, Proceedings, Western Snow Conference, Boulder City, Nevada, pp. 65-70, April, 1950.

Gunn, R., A vertical shaft for the production of thick artificial clouds and for the study of precipitation mechanisms, Journal of Applied Physics, v. 23 pp. 1-5, 1952.

Hall, Ferguson., Status of Possibilities of Artificial Precipitation., Transactions, American Geophysical Union, Vol. 33, No. 6, pp. 866-870, December, 1952.

Hall, F., T. J. Henderson, and S. A. Cundiff, Cloud seeding operations in the Bishop Creek, Calif., watershed. U. S. Department of Commerce, Weather Bureau, Research Paper No. 36, 29 pp., January, 1953.

Harrison, H. T., Results of 42 tests of Bradau-Kooser method of fog dispersal (B-K Number 2), United Air Lines, Inc., 156 pp., September 2, 1952.

Hitschfeld, W., Free fall of drops through air, Transactions, of the American Geophysical Union, v. 32, no. 5, pp. 697-700, October, 1951.

Hosler, C. L., Preliminary investigation of condensation nuclei under the electron microscope, Transactions, of the American Geophysical Union, v. 31, no. 5, pt. 1, pp. 707-710, October, 1950.

Hosler, C. L., M. D. Burkhart and H. Neuberger, On the effect of time lapse between sampling and expansion in the Aitken nuclei counter, Bulletin of the American Meteorological Society, v. 33, no. 6, pp. 251-254, June, 1952.

Itoo, K., On the growth of ice crystals in the air, Papers in Meteorology and Geophysics, Meteorological Research Institute, Tokyo, v. 2, no. 3-4, pp. 315-316, 1951.

---., Phenomena of ice crystals in the air (On small ice crystals), Papers in Meteorology and Geophysics, Meteorological Research Institute, Tokyo, v. 2, no. 1, pp. 67-75, 1951.

Jones, R. F., The temperatures at the tops of radar echoes associated with various cloud systems, with discussion, Quarterly Journal of the Royal Meteorological Society, v. 76, no. 329, pp. 312-336, 1950.

Junge, C., Das Wachstum der Kondensationskerne, mit der relativen Feuchtigkeit Annalen der Meteorologie, v. 3, no. 5/6 pp. 129-135, 1950.

Köhler, H., On the problem of condensation in the atmosphere, Nova Acta Regalis Societas Scientiae Upsaliensis, v. 14, no. 9, 75pp., 1950.

Kraus, E. B., and B. Smith, Theoretical aspects of cloud drop distributions, Australian Journal of Scientific Research, Series A-Physical Sciences, v 2, no. 3, pp. 376-388, 1949.

Krick, I. P., Increasing water resources through weather modification, Speech before American Water Works Association, May 7, 1952, Published by Water Resources Development Corporation, 16 pp., 1952.

---., Report on the meteorological aspects of artificial nucleation in the San Diego mountain area, Unpublished, 31 pp., July 1948; Supplement #1, 14 pp. September 10, 1948.

Krick, I. P., and T.B. Smith, Some evaluations of sustained cloud-seeding operations, Transactions, of the American Geophysical Union, v. 33, no. 1, pp. 53-56, February, 1952.

Krystanov, L. , A case of the enlargement of cloud drops by fusion, Dokl. Akademiia Nauk SSSR, v. 76, no. 1, pp. 53-56, 1951 (In Russian).

Lacaze, J., Theory of formation of descending currents of cumulo-nimbus, Revue Scientifique, Paris, v. 88, pp. 195-201, 1950 (in French).

Langmuir, I., Analysis of the effects of periodic seeding of the atmosphere with silver iodide, Project cirrus, Final Report, Part II, General Electric Research Laboratory, 340 pp., May, 1953.

Levine, J., Statistical explanation of spontaneous freezing of water droplets, National Advisory Council for Aeronautics, Technical Note 2234, December, 1950.

Lieberman, G. J., An evaluation of the 1951-1952 cloud-seeding experiment in Santa Clara County, Stanford University, 21 pp., February, 1953 (Unpublished).

Ludlam, F. H., Structure of shower clouds, Nature, v. 167, no. 4242, pp. 254-256, 1951.

Mason, B. J., Natural and artificial production of precipitation in the atmosphere, Nature, v. 168, pp. 533-534, September 29, 1951.

Miyake, Y., The chemical nature of the saline matter in the atmosphere, Geophysical Magazine, Tokyo, v. 16, no. 2, pp. 54-65, 1948.

Miyake, Y., and Y. Sugiura, The mechanism of dissolution of the atmospheric chloride into rain water, Papers in Meteorology and Geophysics, Meteorological Research Institute, Tokyo, v. 1, no. 2-4, pp. 222-226, 1950.

Mortola, L. S., La microfisica delle nubi ad il contrallo artificiale delle precipitazioni, Geofisica e Meteorologia, v. 1, no. 1, pp. 3-6, 1953.

National Weather Improvement Association, Inc., Weather modification operations analysis program. Minutes of meeting, Denver, Colo., July 12, 1952, 15 pp. (Unpublished).

Nolan, P. J., and P. G. Tedde, Condensation nuclei and meteorological elements in Dublin, Archiv für Meteorologie, Geophysik und Bioklinatologic, Serie A, v. 2, no. 4 pp. 374-385, 1950.

North American Weather Consultants, Report on cloud seeding operations in Santa Barbara County during the period November 1951 - May, 1952. Report 6-6, 19 pp. plus plates and tables, August, 1952.

---., Storm survey report, January 11-20, 1952 (Santa Barbara County), Report 66-1, 27 pp., April, 1952.

Ogiwara, S., Crystallization and freezing of aqueous condensation nucleus, Scientific Reports, Tôhoku University, Series 5, Geophysics, v. 4, no. 1, pp. 24-30, 1952.

---., On the solid condensation nucleus which is not soluble in water (Studies on the formation of cloud and rain, III), Scientific Reports, Tôhoku University, Series 5, Geophysics, v. 2, no. 3 pp. 158-162, 1950.

Ohta, S., Investigations on condensation nuclei (abstract) I - IV, Geophysical Magazine, Tokyo, v. 21, pp. 208-214, 1950.

Otani, S., Theoretical aspect of size distribution of cloud particles and its application to stratus cloud, Geophysical Magazine, Tokyo, v. 23, no. 1, pp. 65-71, 1951.

Ouchi, K., On the stability of the ice germs in a cloud (fog) particles, Scientific Reports, Tôhoku University, Series 5, Geophysics, v. 2, no. 3, pp. 163-166, 1950.

Pérez Siliceo, E., Estudios meteorológicos, 1952, Mexican Light and Power Company, Ltd., 7 pp. plates, December, 1952 (Unpublished).

Pérez, Siliceo, E., and A. Ahumada, Artificial rain, report and evaluation, 1950, Mexican Light and Power Company, Ltd., 17 pp., plates and supplement (Unpublished).

---., Lluvia artificial, informe y evaluación, 1951, Mexican Light and Power Company, Ltd., 12 pp., plates and supplements (Unpublished).

Pollak, L. W., and T. Murphy, Sampling of condensation nuclei by means of a mobile photoelectric counter, Archiv für Meteorologie, Geophysie und Bioklimatologie, Serie A, Meteorologie und Geophysie, v. 5, no. 1, pp. 100-119, 1952.

Rao, Y. P., and E. V. Chelam, Vertical velocity and rainfall by convergence due to latitude effect, Indian Journal of Meteorology and Geophysics, v. 2, no. 2, pp. 121-126, 1951.

Reiss, H., Time lag in the nucleation of supercooled water clouds by silver-iodide smokes, Journal of Chemistry and Physics, v. 18, pp. 529-533, April, 1950.

Research Department, California State Chamber of Commerce, Scientific, economic and legal aspects of weather modification. Unpublished, February 7, 1951.

Reynolds, S. E., Thunderstorm-precipitation growth and electrical-charge generation, Bulletin of the American Meteorological Society, v. 34, no. 3, pp. 117-123, March, 1953.

Sachs, M. S., C. C. McDonald, W. V. Garstka, and H. C. S. Thom, Report on Bonneville Power Administration cloud-seeding operations. United States Department of the Interior, 94 pp., July, 1952.

Schaefer, V. J., Laboratory field, and flight experiments, Project Cirrus, Final Report, Part I, General Electric Research Laboratory, 170 pp., March, 1953.

Schwerdtfeger, W., Compensacion global de la precipitación anual en relación con la producción artificial de lluvias, Meteoros, v. 1, no. 2-3, pp. 189-197, 1951.

Smith, E. J., The influence of meteorological conditions on rainmaking in the Sydney area, Australian Journal of Scientific Research, Series A - Physical Sciences, v. 5, no. 1, pp. 87-103, 1952.

---., Observation of precipitation with an airborne radar, Australian Journal of Scientific Research Series A - Physical Sciences, v. 3, no. 2, pp. 214-223, 1950.

---., Observations of rain from non-freezing clouds, Quarterly Journal of the Royal Meteorological Society, v. 77, no. 331, pp. 33-43, January, 1951.

Squires, P., The growth of cloud drops by condensation, Part I, General characteristics, Australian Journal of Scientific Research, Series A Physical Sciences, v. 5, no. 1, pp. 59-86, 1952. Part II, The formation of large cloud drops, Ibid., v. 5, no. 3, pp. 473-499, 1952.

Squires, P., and C. A. Gillespie, A cloud-droplet sampler for use on aircraft, Quarterly Journal of the Royal Meteorological Society, v. 78, no. 337, pp. 387-393, July, 1952.

Stidd, C. K., Cube-root-normal precipitation distributions, Transactions, American Geophysical Union, v. 34, no. 1, pp. 31-35, February, 1953.

Stone, N. C., and L. O. Grant, Evaluation of cloud seeding by physical and synoptic approaches, Paper at 116th national meeting of American Meteorological Society, Corvallis, Oregon, June 17, 1952, 9 pp., plates (Unpublished)

Strickler, R. F., in collaboration with L. T. Irish, A preliminary investigation of the artificial nucleation of clouds in Southern California. Thesis, California Institute of Technology, 81 pp., 1948 (Unpublished).

Syōno, S., On the vortical rain, Geophysical Notes, Tokyo University, v. 3, no. 25, 3 pp., 1950.

Tsuji, M., On the rate of evaporation and condensation of falling drops, Geophysical Magazine, Tokyo, v. 22, no. 1, pp. 11-14, 1950.

---., On the rate of evaporation of water drops, Journal of the Meteorological Society of Japan, v. 28, no. 4, pp. 119-121, 1950 (in Japanese).

---., On the saturated vapor pressure of small drops of aqueous solution, Journal of the Meteorological Society of Japan, v. 27, no. 11, pp. 345-350, 1949 (in Japanese).

Twomey, S., On the measurement of rainfall intensity by radar, Journal of Meteorology, v. 10, no. 1, pp. 65-67, February, 1953.

United States Weather Bureau, Tentative plans for Weather Bureau artificial cloud nucleation (ACN) project, Department of Commerce, 18 pp., 1 map, November, 1952 (processed).

Vonnegut, B., and R. L. Neubauer, Counting sodium-containing particles in the atmosphere by their spectral emission in a hydrogen flame, Bulletin of the American Meteorological Society, v. 34, no. 4, pp. 163-169, April, 1953.

---., Detection and measurement of aerosol particles by use of an electrically heated filament, Project Cirrus, General Electric Research Laboratory, Occasional Report No. 29, 18 pp., September 1, 1951.

Warner, J., and E. G. Bowen, A new method of studying the fine structure of air movements in the free atmosphere, Tellus, v. 5, no. 1, pp. 36-41, February, 1953.

Warner, J., and T. D. Newnham, A new method of measurement of cloud-water content, Quarterly Journal of the Royal Meteorological Society, v. 78, no. 335, pp. 46-52, January, 1952.

Water Resources Development Corporation, Analysis of cloud seeding operations for Northwest Nebraska Water Resources Development Corp., May 15 - October 12, 1951. Report No. 105, 1952.

---., Preliminary storm analysis for storm of March 9, 10, 11, 1952, for OT-1 Project (Oklahoma-Texas panhandle).

---., Preliminary storm analysis for storm of March 9,10, 1952, for T-5 Project (Waco, Texas).

---., Washington-Oregon individual storm studies for June, 1952, Report No. 303, 1952.

Weiss , L. L., Moisture accumulation rates in Thunderstorm cells, Transactions of the American Geophysical Union, v. 33, no. 1, pp. 13-20, 1952.

West, J. A., A narrative report of flood flows on the Salt, Tonto and Verde Rivers in relation to artificial inducement of precipitation by airplane, spring and summer, 1950, Salt River Valley Water Users' Association, Hydrographic Division, September 15, 1950, (Unpublished).

Workman, E. J., and S. E. Reynolds, Electrical phenomena occuring during the freezing of dilute aqueous solutions and their possible relationship to thunderstorm electricity, Physical Reviews, May 1, 1950.

Yamamoto, G., and A. Miura, Saturation vapor pressure and size of condensation nucleus, Scientific Reports, Tôhoku University, Series 5, Geophysics, v. 3, no. 1, pp. 34-39, 1951.

APPENDIX C

ON THE METHODOLOGY OF EVALUATING CLOUD SEEDING OPERATIONS

A Report to the Division of Water Resources,
Department of Public Works of the State of California,
on Part of the Work Performed at the
Statistical Laboratory, University of California
Berkeley, California

This report was prepared with partial
support from the Office of Naval Research

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April, 1953

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ON THE METHODOLOGY OF EVALUATING CLOUD SEEDING OPERATIONS

(revised October, 1953)

A report to the Division of Water Resources,
Department of Public Works of the State of California
on part of the work performed at the
Statistical Laboratory, University of California
Berkeley, California

By T. A. Jeeves, L. LeCam, J. Neyman and E. L. Scott

Note: This report is a revision of an earlier report under the same title submitted in March of 1953. The earlier report did not include the analysis of the 1951/52 operations because the Weather Bureau, due to financial restrictions, had not been able to publish the precipitation data. We are indebted to Mr. Hugh A. Spangler, of the Weather Bureau, for enabling us to obtain these data in advance of publication, and to Mrs. M. Vasilevskis, of the Statistical Laboratory of the University of California, who carried out the necessary computations.

Summary

The report presents (i) a critical analysis of two frequently used methods of evaluating cloud seeding operations, the method of percent of normal and the regression method, (ii) brings out what appears to be a common but thus far unnoticed phenomenon, namely, that the relation between the rainfall in two adjoining areas (target and control) varies from one type of storm to another, (iii) a suggested modification of the regression method, (iv) an analysis of the Carrizo Plain cloud seeding operations of 1950/51 and of 1951/52 by means of the modified method of regression, and (v) an outline of an experiment capable of producing real documentary evidence of the effectiveness of cloud seeding.

The cloud seeding operations in Santa Barbara County and in the Southern Sierra have also been analyzed by the modified regression method. These analyses are presented elsewhere.

(i) The first method of evaluation, that of "percent of normal" was found to be entirely unreliable. The second method of evaluation, the regression method, was found much more promising than the first but still open to criticism and doubts.

(ii) The doubts just mentioned are related to the apparently common phenomenon of different regression equations for different types of storms. This means that the equation connecting the average precipitation in the target area with the precipitation in the control area changes from one type of storm to another. This phenomenon appears to be demonstrated in the Carrizo Plain area, in Southern Sierra, in Santa Clara County, and in Santa Barbara County.

(iii) Because of the dependence of the regression equation mentioned above on the type of storm, it is suggested that the regression method of evaluation be applied not to the totality of all storms taken together but to the particular classes of storms that may be identified by a preceding analysis by a competent meteorologist. The advantages of such modification of the regression method are illustrated using the classification of storms devised by Mr. Edward M. Vernon, U. S. Weather Bureau, San Francisco, California.

(iv) The analysis of the Carrizo Plain operations of 1950/51 using the modified regression method based on Mr. Vernon's classification of storms, indicates that (a) the seeding of storms of class A probably resulted in an increase in the seasonal precipitation of about 0.47 inches; (b) that the seeding of storms of class B probably resulted in a decrease in the seasonal precipitation of about 0.78 inches, and (c) that the seeding of storms of class C probably resulted in a decrease in the seasonal precipitation of about 0.12 inches. Thus, the total probable result of the cloud seeding appears to be a decrease of about 0.43 inches for the season.

The analysis of the 1951/52 operations, however, indicates (a) a decrease of about 0.26 inches for class A storms; (b) an increase of about 0.57 inches for type B; and (c) a decrease of about 0.42 inches for class C. Thus, the total result is a decrease of about 0.11 inches.

The uncertainty of these conclusions is connected with the uncertainty that the classification of storms used is "sufficient," in the sense that the three classes A, B and C, could be split into subclasses of storms with different properties. Such uncertainty will always be connected with any method of analysis other than of data provided by a randomized experiment.

(v) Since the area under contracts for cloud seeding continues to expand and thus the importance of evaluating these operations continues to grow, finally, since the organization of a randomized experiment, capable of producing documentary evidence of the effectiveness of cloud seeding is both simple and inexpensive, it is suggested that the contracts between the weather modification companies and the consumers include a clause that would incorporate into the commercial cloud seeding a randomized experiment. The report ends with a brief outline of the experiment and of the suggested clause.

Respectfully submitted,

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ON THE METHODOLOGY OF EVALUATING CLOUD SEEDING OPERATIONS

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1. Introduction. The present paper originates from the work at the Statistical Laboratory conducted under contract with the Division of Water Resources, Department of Public Works of the State of California. The project includes a critical review of methods of evaluating cloud seeding operations and a study of methods capable of producing documentary evidence as to whether or not current commercial cloud seeding operations increase precipitation. The paper summarizes the results thus far obtained. A part of these results was presented at the joint meeting of the Institute of Mathematical Statistics, the American Geophysical Union and the American Meteorological Society held in East Lansing, Michigan, in September, 1952. Further results were reported at the meeting of the American Meteorological Society in Santa Barbara, California, in June, 1953.

Among the methods of evaluating cloud seeding operations found in the current literature the following were reviewed.

(i) Analysis of the "percent of normal" precipitation per storm, observed following cloud seeding operations.

(ii) Comparison of seeded precipitation in the target area with the value computed from a linear regression of the unseeded precipitation in the target area on the precipitation in one or more control areas. For the sake of brevity, this method will be labeled the "regression method."

Although both methods are frequently used, they appear to be of very different weight and most of the present paper is concerned with the regression method. The last part of the paper is given to the discussion of a randomized experiment on cloud seeding, which alone can give a decisive answer to the question whether or not the seeding of clouds as practiced now can increase precipitation.

2. Method of percent of normal precipitation. The essence of method (i) is illustrated in Figures 1 and 2 taken from a recent report of a commercial cloud seeding company. For a given month the long run average precipitation is determined for a number of rain gages in the target and surrounding areas. These long run averages, covering periods of at least 10 years, are described as "normal" precipitations for the given month. At each station the precipitation from a seeded storm is expressed as a percentage of the monthly normal. These percentages are marked on the map and curves of equal percentage of normal precipitations are drawn among these points. A typical analysis of these curves reads more or less as follows: "In the absence of cloud seeding one would expect that the percentage of normal precipitation computed for a storm will vary from station to station within very narrow limits. For this particular seeded storm the percent of normal precipitation varies considerably. Thus, this variation is ascribable to cloud seeding. In particular, it is seen that some parts of the target received more than twice as much rain as certain areas outside of the target," etc. Thereafter, the reader is referred to graphs, similar to those exhibited in Figures 1 and 2. Here the authors of the reports indicate areas where effects of seeding are considered definitely certain and also those where such effects appear to be absent.

This type of argument has been used very extensively by commercial concerns engaged in cloud seeding. Unfortunately, as was shown in a recent report (1), the basic premise of the argument, viz. "In the absence of cloud

seeding one would expect that the percentage of normal precipitation computed for a storm will vary from station to station within very narrow limits," is in contradiction with the facts. An analysis of isopercent of normal curves was performed for all storms during the year preceding the first year of seeding operations in the particular area and it was found that a wide variation of the percent of normal precipitation is a most usual phenomenon. Figure 3 exemplifies the results of this study in relation to the San Diego area, the same as the area envisaged in Figures 1 and 2.

Because of these facts, it must be recognized that the claims of effects of cloud seeding resulting from the application of the method just described are baseless. However, the method appears to have a substantial advertising value.

3. Method of regression. The method of evaluation of commercial cloud seeding operations that now is most frequently used is the regression method. In the opinion of the members of the Statistical Laboratory, this method is the most promising out of those in actual use. However, on closer examination, it also was found to be open to criticism and doubts. Some of the reasons for our skepticism are hypothetical. For some others we have documentary evidence.

The method consists in comparing simultaneous precipitation observed in the target of seeding operations and in one or more adjoining comparison areas. For purposes of explaining the essence of the method and of pointing out some of its weaknesses it will be sufficient to consider the case of just one comparison area.

Consider, then, a target and a control area so selected that, presumably, the seeding operations meant to increase precipitation in the target do not affect the control. Several rain gages are located both in the target and in the control areas. Select a convenient unit of observation. This may be a single storm or a fixed period of time, 24 hours, a week or a month, during

which there is some precipitation over the control area. Denote by X the average rainfall recorded by the gages of the control area during the unit of observation and by Y a similar average computed for the target and for the same unit of observation.

Using the existing records for years when no seeding operations were performed, a series of simultaneous values, say (x_1,y_1), (x_2,y_2),..., of X and Y is compiled which characterizes the relationship between the normal (unseeded) precipitation in the target and in the control. A simple scatter diagram is illustrative of the rate at which a unit increase of precipitation in the control is accompanied by an increase in precipitation in the target. However, ordinarily the reports go farther and produce regression lines, most frequently straight regression lines,

$$Y(x) = A + Bx$$

of the precipitation in the target on that in the comparison area. As is well known, the value of Y(x) computed for any given x represents an approximation to the average rainfall in the target in those cases when the average precipitation X in the control is exactly equal to x.

We emphasize that the computations of the regression Y(x) are based on all data available for the years before cloud seeding. Now denote by y^* the rainfall in the target recorded during the unit time of observation when the clouds were seeded, and let x^* stand for the corresponding rainfall in the control area.

In order to evaluate the effect of seeding, we substitute x^* instead of x into the regression equation and obtain

$$Y(x^*) = A + Bx^*$$

which is interpreted as the approximate average value of the precipitation in the target that one would expect without cloud seeding. This value is then compared with the observed value y^* and the difference $y^* - Y(x^*)$ is treated

as an estimate of the effect of seeding. If this difference is positive and large enough to suggest the impossibility of its being due to purely random variation, then the claim is made that the beneficial effect of seeding is proved. In order to support this claim the theory of testing statistical hypotheses is used and the probability computed that a deviation of the observed or larger size will arise as a result of random variation alone.

Ordinarily, the reports on seeding operations are concerned not with just one but with a number of units of observation. Then the above analysis is repeated for every unit and a general conclusion is based on all the differences of the type $y^* - Y(x^*)$ that were computed. It happens occasionally that the favorable conclusion regarding the effect of seeding is based not so much on the size of the differences $y^* - Y(x^*)$ as on the fact that, although of moderate magnitude, such differences are predominantly positive.

As mentioned, the method just described is sounder than any other we have seen applied thus far. However, it is open to a number of objections. Some of these objections, of technical nature, are directed against the way in which the method is used rather than against the method itself. Some other objections apply to the method.

4. Technical objections against the customary way of using the regression method. Our first objection is technical. The statistical test commonly used as just described is based on the so called normal theory and for its validity certain conditions must be satisfied. Ordinarily, no attempt is made to study this point. One of the conditions is that the degree of variability of the non-seeded rainfall in the target about the regression line be the same whether the rainfall in the control is small or large. In the cases we studied this condition was not satisfied and the variation of Y when the value of X is large was found to be substantially greater than in cases when X is small.

To offset this, one may think of performing the regression analysis not with X and Y directly, but with appropriately selected functions of these variables such as, for example, X and Y. A number of trials worked out at the Statistical Laboratory indicated that the regression of Y on X is approximately linear and that the conditional variance of Y given X does not change very much. As a result, the square root transformation is regularly used in our work. However, certain difficulties must be mentioned.

Suppose that as a result of the application of the test it is decided that the expectation of Y^* is greater than that computed from the regression line, namely

$$A + B\ X^* \ .$$

Then there will immediately arise the question as to the extimate of the excess in precipitation over the target that may be ascribed to the effect of seeding. The proper answer seems to be as follows. According to a familiar formula, the expectation of a square of a random variable is equal to the square of the expectation of its first power increased by the variance of the variable. Applying this to the square root of the average precipitation in the target, supposed to have a linear regression on the square root of that in the control, we obtain the following expression for the expected unseeded average rainfall in the target

$$(A + Bx^*)^2 + \sigma^2_{Y|X}$$

Thus, the excess of the seeded precipitation over what would be normally expected without seeding is given by

$$y^* - (A + Bx^*)^2 - \sigma^2_{Y|X}$$

where the last term is estimated in the course of the familiar process of obtaining regression equation. This formula is used below in order to estimate

the presumed average effect of cloud seeding.

Another objection against the way of using the regression method (ii) is concerned with the selection of the control area. Figure 4 gives a map of the Los Angeles area in which extensive seeding operations were conducted recently. The general target area and also a comparison area (on the coast and on some islands) are marked on this map. Also the positions of the silver iodide generators are marked with dots and diamonds. It will be seen that some of the generators were working in the area of comparison. There now seems to be a general consensus of opinion that in the immediate vicinity of generators the clouds may well be overseeded so that the precipitation from these clouds is decreased. If this be so then the area of comparison in these particular operations must have received less than normal precipitation. At the very least, it may be presumed that the precipitation in this area may have been affected by the cloud seeding. For this reason, the precipitation for the target computed from the regression equation can hardly be considered an appropriate measure of what should be normally expected for a given storm.

The above objection is, of course, hypothetical. However, until the hypothesis that the seeding affects the comparison area is disproved, the objection stands.

5. An essential weakness of the regression method. Preliminary remarks. Our third objection is directed at the regression method itself. Since the regression equations used are based on the totality of data on precipitation amounts in the target and in the control area observed in the past, the validity of the method depends on whether or not the same equations are applicable to every particular storm to be observed in the future.

Guided by experience with other phenomena, the authors have most serious doubts whether this is true. As is well known, the pattern of the weather changes substantially from one year to the next and from one decade to the

following. It is common to speak of series of dry years and of series of wet years. Undoubtedly, this kind of description applies primarily to the total amounts of precipitation. However, on purely a priori grounds, one is led to expect that within the totality of storms passing over a given locality it is possible to distinguish several categories or types which, in addition to possible differences in total amounts, differ from each other in the pattern in which the precipitation is distributed over the given locality. This difference in the pattern will then be reflected in the position of the regression line of the unseeded rainfall in the target on that in the control area so that to each type of storm there will correspond a special regression line, different from those corresponding to other types.

If such different types of storms exist then what is loosely called the pattern of weather during a given year may be characterized by the proportions of storms of different types. If these proportions change from one year to the next, then the summary regression line, computed for a past decade, need not be applicable to the next year. In such circumstances no statistical technique can guard against the misleading conclusions that may result from the application of the regression method. In fact, the application of a statistical test can only indicate that the observed differences of the type $y^{*} - Y(x^{*})$ can hardly be ascribed to chance alone, but it will give no suggestion as to whether the suspected non-chance element is the cloud seeding or the prevalence of storms of a particular type.

For these reasons, the Statistical Laboratory adopted a cautious attitude towards the evaluations of cloud seeding operations based on the regression method. Also, some work was done to substantiate the hypothesis that the different types of storms, with different regression lines, are a reality. This is described in the next section.

6. Existence of types of storms with different regressions. It must be obvious that the search for types of storms with varying regressions of the rainfall in the target on that in the control area must begin with the formulation of a plausible hypothesis regarding the machinery of the phenomenon. This machinery may vary from one area to the next and, therefore, the hypothesis must be adjusted to the particular target and to the particular control area. When a hypothesis of this kind is formulated, the subsequent statistical analysis may suggest ways of improving it.

Work of this kind was done for several areas in California and is still in progress. At the present moment it is already possible to report on some significant results relating to the Carrizo Plain where in the seasons 1950/51 and 1951/52 there were extensive seeding operations.

In order to explain our first working hypothesis regarding the machinery of the change in the regression of rain in the target on that in the control we must begin by describing the location of the two areas.

The Carrizo Plain is a plateau located west of Bakersfield, California, just east of the Coastal Range which screens it from the Pacific Ocean to the west. Also there is to the south of the Carrizo Plain a substantial barrier of mountains separating it from the influence of the ocean from that direction. In order to apply the regression method to the evaluation of cloud seeding operations in the Carrizo Plain it was necessary to select a suitable control area. For this purpose, this area has to be not very far from the target and, at the same time, it should be unaffected by cloud seeding operations. The only area satisfying both these conditions to a reasonable extent was found to be the narrow strip of land along the Pacific Ocean, just west of the Coastal Range.

Unfortunately, the two areas were found to contain only seven rain gages with reliable hourly records going back to 1940/41. Of these, Cholame,

Lost Hills, and Taft are located in the target and Huasna, Paso Robles, San Luis Obispo and Santa Maria in the control. It will be realized that, strictly speaking, whatever we say about the target and the control area, applies to the two combinations of three and of four stations, respectively, just enumerated, rather than to the whole areas, the target and the control.

Furthermore, during the 1951/52 season Santa Maria itself was part of the target area for extensive cloud seeding operations in Santa Barbara County. Thus, Santa Maria had to be deleted from the control area, leaving only three stations for the 1951/52 season. In order to be able to compare the efficiency of the cloud seeding in the successive seasons, the final results in the present report are based on the revised analysis, comparing the three target stations with three control stations. However, certain preliminary studies compare the three target stations with four control stations.

The first hypothesis regarding the machinery of the dependence of the regression on the type of storm was formulated for us by Mr. Arnold Court, to whom we are greatly indebted. As already mentioned, the target stations are, more or less, surrounded by mountains. The stations in the control are entirely open to the influence of the ocean from the west, but not so much from the south. In order to realize the implications of these topographical relations, we recall the familiar fact that the winds from the ocean deposit more precipitation on the windward slopes of the mountains than on the lee slopes. Now, visualize two groups of storms over Southern California, one bringing the moisture from the west and the other from the south, but all depositing the same amount of precipitation in the coastal control area. Since the southerly storms bring the moisture to the control over a ridge of mountains, while no such obstacle exists for the westerly storms, the southerly storms of the group considered must be generally wetter than the westerly storms. Therefore, they may be expected to bring more rain to the target than

the storms of the westerly group. As a final result, the regression line of the rainfall in the target on that in the control corresponding to southerly or to southwesterly storms was expected to lie above that corresponding to westerly storms.

Starting with this tentative hypothesis, an effort was made to classify the storms according to the direction of the wind. The unit of observation chosen was the 24 hour period midnight to midnight. Only such units of observation were considered in which there was some precipitation recorded in at least one of the four stations in the control. The specific criterion adopted for classification of the units of observation was the wind direction at Santa Maria at the altitude of 10,000 feet, at 2 AM as read from the synoptic map. It was found that during the decade 1940/41 to 1949/50 the wind direction during most of the units of observation was either westerly or southwesterly. Consequently, the details of the results obtained will be presented for these two directions only. In order to offset the inequality of the conditional variance, the regressions actually computed refer to square roots of total precipitations rather than to the precipitations themselves.

Figure 5 shows the two regression curves, one for the westerly and the other for the southwesterly storms. The circles connected by broken lines indicate the actual averages computed for the arrays of equal precipitation in the control. It will be seen that the computations fully confirm the hypothesis of Arnold Court. Granting the applicability of the normal theory, the difference between two regression lines is significant.

It must be clear that the classification of storms according to the wind direction at one point read from a synoptic map must be crude. Anyone who has had any contact with such maps is bound to have the impression that the isobars drawn on them are occasionally based on the interpolation by meteorologists rather than on actual measurements. Particularly, this applies to the first

half of the decade studied when the upper air data were missing or unreliable.

For these and similar reasons, efforts were made to refine the basis of classification of storms by using several other characteristics of the weather situation, either separately or in combinations. This was done for the Carrizo Plain and also for two other regions where cloud seeding operations had been in progress, a region in the Southern Sierra and in Santa Clara County.

The particular weather characteristics tried include the following: (a) the height of the 700 mb. surface over Santa Maria, labeled "high" if the height exceeded the approximate median of 3021 meters and "low" otherwise; (b) whether or not there was some rain recorded in the S.E. Farallon Island the day before; (c) the pressure difference in San Francisco and in Santa Maria, labeled "high" or "low" according to the relation to the median. A number of combinations of these characteristics was found for which the regression lines of the precipitation in the target on that in the appropriate control differ significantly. Figures 6 and 7 exemplify the results obtained.

Although these further attempts to classify the storms are more elaborate than the original attempt using the direction of the wind at 10,000 altitude, they are still crude and amateurish. However, since even such crude methods show significant results in every locality in California in which they were tried, it seems very probable that the dependence of the position of the regression line on the type of storm is a common phenomenon. At least this seems to apply to regions like California, where the weather is subject to combined influences of mountains and of the nearby ocean.

7. Classification of storms by Edward M. Vernon. After the existence of types of storms, with different regressions of rainfall in the target on that in the control was established (or, at least, made extremely probable), the good services of the Division of Water Resources, Department of Public Works

of the State of California were sought in order to obtain the cooperation of an outstanding meteorologist so that a more refined classification of storms could be devised.

Accordingly, the Division of Water Resources approached separately Professor Morris Neiburger, of the University of California at Los Angeles and Mr. Edward M. Vernon, of the United States Weather Bureau, San Francisco, California. Both readily agreed to cooperate and produced classifications of storms. At the present moment it is possible to report on the results obtained in the Statistical Laboratory using the classification of Mr. Vernon.

The results of Mr. Vernon's work may amount to a discovery of substantial consequence. For this reason, the details of his classification will be left for him to publish in the form he thinks fit. The present section is meant to present the working of the classification. We mention only that the units of observation are no longer the stiff 24-hour periods from midnight to midnight and that the criteria for classification are more elaborate than the mere direction of wind and/or the height of the 700 mb. surface. However, these criteria, involving both qualitative and quantitative characteristics, are as objective as they can possibly be and, once established, the classification of units of observation is purely clerical. Unfortunately, some of the data needed for the classification are available only for the period beginning with 1945/46. Therefore, the regression analysis had to be limited to the quinquennium, 1945/46 to 1949/50.

Actually, Mr. Vernon proposed not one but two classifications of storms (really of units of observation; however, we shall use the word storm as a convenient synonym), and it is interesting to present both.

The first classification contemplated two qualitatively different main classes of storms, marked with Roman numerals I and II, each subdivided into three subclasses, Ia, Ib, Ic and IIa, IIb, and IIc. On <u>a priori</u> grounds it

was anticipated that storms of class I will be, so to speak, more favorable to the target than storms of class II. In other words, it was anticipated that the regression of the precipitation in the target on that in the control area, corresponding to storms of class I will lie above that corresponding to class II. This difference was expected to be most pronounced in relation to the subclasses Ia and IIa, a little less pronounced for the subclasses Ib and IIb and only slight for the subclasses Ic and IIc. Thus, visualizing the six regression lines of the rainfall in the target on that in the control, it was expected that all three lines corresponding to class I would lie above the three lines corresponding to class II, with the lines of subclasses Ia and IIa being on the two extremes, those of subclasses Ib and IIb being intermediate and, finally, those of subclasses Ic and IIc taking the central position in the sextuplet.

It happens but extremely rarely that an a priori hypothesis regarding a complex natural phenomenon hits a bull's eye. Therefore, one should not be surprised that the actual computations performed for the six subclasses did not agree exactly with anticipation. The six regression lines are reproduced in Figure 8 and it will be seen that they conform with Mr. Vernon's hypothesis only partly. As expected, the types Ia and IIa are at the two extremes and, on the whole, the regressions corresponding to the subclasses b and c follow each other in the order that was anticipated. However, in certain cases the differences are small and non-significant. Furthermore, and this is contrary to the original hypothesis, the two triplets of the regression lines corresponding to the basic categories I and II do not lie one above the other but overlap somewhat.

When this result was obtained, a new, so to speak, a posteriori classification of storms was proposed in which the original class IIc was split into three parts, according to the direction of the wind in the upper air, and

portioned out among the three classes Ia, Ib and Ic. The second classification system was made up of five classes: Ia' = original Ia plus one part of IIc; Ib' = original Ib plus another part of IIc; Ic' = Ic plus remaining part of IIc; and the original classes IIa and IIb.

However, for the data available, the differences between the classes Ia' and Ib' do not appear to be significant so that they were combined into one class labeled class A. Similarly, the two classes Ic' and IIb were combined to form a composite class B. Then, for convenience in description, the class C coincides with the original extreme subclass IIa. Figure 9a presents the results of this third classification in the form of three regression lines. These three lines appear to be quite distinct, one from another, and the standard statistical tests indicate that they are different lines. However, the standard tests are not really applicable since we would be asking several questions, one after another, of the same data. We should ask the questions simultaneously. A new technique, that of simultaneous confidence bands, was developed for this problem.

Figure 9b shows the simultaneous confidence bands for the three regression lines. We must keep in mind that we shall never know where the true regression lines are; all that we can obtain are estimates. However, we can obtain a confidence band for each true line. The simultaneous 50 percent confidence bands have the property that when we state that a true line is within its band, the probability that we are correct, for every line and for every value of the precipitation in the control area, is .50. Notice that we are very strict in assessing errors: if only one of the lines were outside its band at only one point, this would be recorded as an error. Thus, wherever any of the confidence bands do not overlap, we can state with confidence in the truthfulness of our statement: The true lines are different.

We wish to emphasize that the criteria used to classify the storms do not consist in any part of the precipitation in the target nor of the precipitation in the control area. We have here an independent system of classification which allows us to predict whether a storm will be more favorable, or less favorable, or average in bringing precipitation to the target.

We wish to remark that the third classification of Mr. Vernon may or may not be preferable to his original one and the decision may be reached only after some experience with new data. If the original classification were based on the numerical value of a single weather characteristic such as, for example, the height of the 700 mb. surface at a given point, then there would hardly be any objection against the merging of two or more continuous classes of storms for which the regression lines are very nearly the same. However, in the present case the situation is a little different. It may be compared with the differentiation of man according to the relation between some two measurements of the body. Thus, for example, one may think first of one single regression line for the population of Ireland to be compared with a single regression line for the population of Spain. Then one could think of the refinement in the analysis leading to two regression lines for Ireland, one corresponding to people with black eyes and the other to the rest of the population. With reference to the Spanish Armada, one finds it plausible that the regression line for the dark eyed Irishmen may conceivably be similar to that for the population of Spain, in which case one may think of computing just one regression for the two particular characteristics to apply to both the Spaniards and to Irishmen with dark eyes. According to the amount of data available for the calculation of regressions, this may or may not be advisable. However, it would certainly be very hasty to conclude that, because of the similarity of the regression between some two particular characteristics, the dark eyed Irishmen are indistinguishable from the Spaniards in all other respects.

Similarly, as far as the immediate purpose of evaluating the cloud seeding operations is concerned, it is difficult to raise any objection against using the regression lines of Figure 9 relating to classes of storms A, B and C. On the other hand, in the further analysis of the phenomenon, it is probably advisable to keep in sight the original classes and their three subclasses of Mr. Vernon. Later on we shall have occasion to return to this particular point.

Mr. Vernon's classifications were subjected to further study in order to determine whether or not, as was the case with the original classification of storms according to the wind direction at the 10,000 feet altitude, it is possible to improve on it by means of some additional criterion of classification. Contrary to what was found in relation to the classification according to the direction of the wind, our efforts were unsuccessful. Therefore, it looks as if Mr. Vernon's criterion is approximately what is known in statistics as sufficient. Whatever one adds to it has no effect on the accuracy of predicting the average rainfall in the target for units of observation with known rainfall in the control area. Naturally, however, our failure to find the characteristics of storms improving Mr. Vernon's classification does not mean that no such characteristics exist. This point also will be referred to further below.

8. Essential weakness of the regression method. Continuation. In order to appreciate fully the implications on the regression method of the existence of different types of storms, with differently placed regression lines of the rainfall in the target on that in the control area, it is desirable to refer to Figure 10 and Table I. Figure 10 gives three frequency distributions of directions of wind at 10,000 feet altitude over Santa Maria. The first of these distributions refers to the decade 1940/41-1949/50, the second to the first year of that decade and the last to the first year of cloud seeding operations, 1950/51.

It will be seen that over the decade 1940/41-1949/50 the relative frequency of units of observation with westerly winds is almost exactly equal to that corresponding to southwesterly winds. Thus, the regression line of the precipitation in the target on that in the control area runs between the two curves exhibited in Figure 5. In the years 1940/41 and 1950/51 the situation is different. The two most relevant directions of wind occur with distinctly unequal frequencies. In the year 1940/41 the prevalent winds are from the southwest, to which there corresponds the higher of the two regression curves in Figure 5. Thus, even if cloud seeding has no effect on precipitation, seeding operations performed in a year like 1940/41 and evaluated by the method of regression would have produced the impression that there is a positive effect.

Contrary to this, the winds prevailing in 1950/51 are predominantly from the westerly direction, corresponding to the lower of the two regressions in Figure 5. Thus, in the absence of any real effect of cloud seeding, evaluation by the regression method of the actual seeding operations conducted in 1950/51 may be expected to indicate that, on the average, these operations diminished the rainfall.

Also, if cloud seeding applied to all storms diminishes or increases the average rainfall, then the shifts in the position of the regression line in 1940/41 and in 1950/51 would tend to hide these effects.

These conclusions refer to the original crude classification of storms over the Carrizo Plain area, based on the direction of winds at 10,000 feet altitude over Santa Maria. Qualitatively the same conclusions are suggested by the results of Mr. Vernon's classification. The relative frequencies of the three types of storms in the quinquennium 1945/46-1949/50 and in the two seeded years 1950/51 and 1951/52 are as follows

Type of Storm	Relation frequency, July 1 to June 30 (or September 1 to May 31)					
	1945/46 to 1949/50		1950/51		1951/52	
A	37.5	(37.4)	29.8	(27.3)	33.9	(30.4)
B	46.6	(45.9)	44.7	(45.4)	52.5	(55.3)
C	15.9	(16.7)	25.5	(27.3)	13.6	(14.3)

It will be seen that in the seeded year there were substantially fewer storms corresponding to the highest of the three regression lines in Figure 9 and that this deficiency was compensated by excesses in frequencies of storms of class B and, particularly, of class C corresponding to the lowest of the three regression lines in Figure 9. Thus, in the absence of any effect of seeding, the regression method applied to the operations of 1950/51 would suggest that seeding is harmful.

The above conclusions apply to the situation where every storm passing over a given locality is seeded. However, most of the weather modification companies do not seed all the storms. Thus, for example, out of the 44 units of observation in 1950/51, in which there was some rain recorded in the control area for the Carrizo Plain, 13 units were definitely not seeded (the information is not clear for two additional units). Thus, it is appropriate to consider the implications of the existence of different classes of storms on the regression method applied to evaluate the seeding operations in which only selected storms are actually seeded.

Here we must make a distinction between the operator who either does not know of the existence of types of storms with varying regression or is not

able to identify them and the operator who does. For the operator who selects storms for seeding without reference to classes like Mr. Vernon's the situation will be very similar to that discussed above in which all storms were assumed to be seeded. For him the outcome of the evaluation by the regression method will be at the mercy of the relative frequency of storms of different types that happen to prevail in the particular season.

Let us now turn to the possibility of an operator who is aware of the existence of types of storms with differently placed regression lines of rain in the target on that in the control and also one who is able to identify these types. In this case, and in the absence of any effect of seeding, any evaluation of the cloud seeding operations that relies on the regression method will be exactly in the position of the Court of King Arthur faced with an eclipse "produced" by the famous Connecticut Yankee. For example, working in the Carrizo Plain, the operator could choose to seed only storms of Mr. Vernon's class A and not seed the others. Since storms of class A have a regression line considerably higher than all the others, the average rainfall from seeded storms will be substantially greater than that expected from the unique regression equation computed from all unseeded storms in the past. Thus, the operator's success in forecasting will be interpreted as a success in artificially increasing precipitation.

This possibility is presented as an argument against the regression method. However, there is no evidence that the storms seeded in the Carrizo Plain operations were selected according to anything like Mr. Vernon's classification.

These, then, are the reasons why the Statistical Laboratory has adopted an attitude of skepticism toward the evaluation of commercial cloud seeding operations by means of the regression method. In the particular form in which it is currently used, that is, with the regression line based on the totality

of historical data, without any classification of storms, this method: (a) may give the impression that the seeding of clouds has a significant effect (positive or negative) when actually no effect is present, and (b) it may fail to discover the existence of an effect when it actually exists and is substantial; finally (c) repeated evaluations of the same cloud seeding operations, perhaps using several regression lines corresponding to two or more longer or shorter periods of observation before the beginning of cloud seeding, may lead to contradictory results.

In this latter connection it is well to recall the recent article (2) by G. W. Brier and I. Enger, concerned with cloud seeding operations in Central Arizona. Using a 10 year period of observation preceding cloud seeding and and the data from 72 stations, the authors found a regression equation indicating a significant positive effect of cloud seeding during the month of April. Also, using a 30 year period of observation at 37 stations, the authors found another regression equation with which the precipitation during the seeded years appears distinctly within the normal limits. The authors end with the somewhat pessimistically worded query as to which of the two results should be given credence.

The rainstorms in Arizona are known to fall into two distinct categories, those coming from the Gulf of Mexico, predominantly occurring during the summer, and those from the Pacific, prevailing in the winter. Most probably, a closer analysis would reveal other types. It is very likely that during the month of April the relative frequencies of these storms vary from year to year and from decade to decade. Thus, it is not impossible that when these varying frequencies are taken into account, the seeming paradox noted by Brier and Enger will disappear.

As a conclusion, the authors suggest that the regression method in its usual form, based on an equation computed from the totality of observations

from the precloud-seeding era, is unreliable and should be abandoned. In general, the authors doubt whether a satisfactory method of evaluating commercial cloud seeding operations is possible unless these operations are remodeled to form a properly designed experiment. However, since some sort of evaluation frequently is necessary, the authors wish to suggest a modification of the old regression method. This modification, described in section 9, presupposes that for the given target and for the given control area a competent meteorological analysis of storms was performed leading to a few well defined classes of storms, with different regression equations of the unseeded rainfall in the target on that in the control area. Then, in order to evaluate a given seeded storm, the precipitation that it brought to the target is compared with the expectation computed from the regression that corresponds to the class to which the given seeded storm belongs. It will be seen that, although failing to produce real documentary evidence either in favor or against the claims of success in cloud seeding, the modified regression method offers interesting possibilities and may give important results.

9. Evaluation of the Carrizo Plain cloud seeding operations in 1950/51 and 1951/52 by the modified regression method. Unfortunately, for reasons understood to be beyond the control of the U.S. Weather Bureau, the regular publication of the hourly precipitation data was interrupted in 1951. Therefore, the analysis of the Carrizo Plain cloud seeding operations for the season, October 1950 to May 1951, inclusive, there were 44 units of observation, as defined by Mr. Vernon, in which there was some precipitation in the control area. Out of these, 29 are known to have been seeded, 13 are known to have been left unseeded and there is doubt about two. During the second season there were 54 units of observation: 33 seeded, 21 unseeded.

The distribution of these 98 units among the categories of Mr. Vernon's two classifications is as follows.

Table I

Original classification of Mr. Vernon's Units of Observation

in the Carrizo Plain, for two seasons

Category	Seeded units		Not seeded units		Doubtful	
	1950/51	51/52	50/51	51/52	50/51	51/52
Ia	4	4	3	5	0	0
Ib	3	2	2	2	0	0
Ic	6	10	3	5	0	0
IIc	4	7	1	5	1	0
IIb	4	6	0	0	1	0
IIa	8	4	4	4	0	0
Totals	29	33	13	21	2	0

Table II

Final classification of Mr. Vernon's Units of Observation

in the Carrizo Plain, for two seasons

Category	Seeded units		Not seeded units		Doubtful	
	1950/51	1951/52	50/51	51/52	50/51	51/52
A	7	7	5	9	0	0
B	14	22	4	8	2	0
C	8	4	4	4	0	0
Totals	29	33	13	21	2	0

It is interesting to note that out of 28 units of category A, with the highest regression of the normal (unseeded) rainfall in the target on that in the control, 14 units were left unseeded. On the other hand, the operators seeded 12 out of the 20 least "promising" units of category C. This suggests that the selection of opportunity for seeding was based on principles entirely different from Mr. Vernon's classification.

In order to emphasize the difference between the regression method in its original form and its modification suggested in the present paper, the Carrizo Plain cloud seeding operations will be subjected to an analysis by both.

Figure 11 gives the results of the analysis by the customary regression method. The straight line shown in the figure is the regression line of the square root of the average (per station) precipitation in the target on the square root of the similar average in the control area, computed from the data on all the 237 units of observation over the unseeded period 1945/46 to 1949/50, irrespective of the class to which these units belong. This regression line is labeled the overall regression line. As usual, only such units of observation were considered in which there was some precipitation in the control area.

The circles (some open, some filled) in Figure 11a correspond to 29 units of observation in 1950/51 that were actually seeded, while Figure 11b corresponds to 33 units in 1951/52. The deviation of each circle from the overall regression line, measured vertically, represents the combination of the unavoidable random variation and of possible nonrandom effects. If the customary regression method is firmly relied on, then any such possible nonrandom effect is identified as the effect of seeding. Examining Figure 11a from this point of view it is easy to see that, if anything, the overall effect of cloud seeding was detrimental and the actual rainfall from the storms seeded in 1950/51 was lower than would have been expected without seeding. Granting

the applicability of the normal theory, the deviations of the seeded precipitation from the regression line are highly significant. The estimated decrease in the precipitation per rain gage, total for the season, amounts to 0.86 inches. Since the long term average seasonal precipitation in the target (average stations Cholame, Lost Hills, Middlewater and Taft) is only 6.42 inches, the presumed loss of 0.85 inches, which the customary regression method would ascribe to cloud seeding, is quite substantial. As indicated in Figure 11b, the overall regression method would also indicate that seeding was detrimental in 1951/52, although by a smaller amount.

It will be instructive to investigate the possible effectiveness of the cloud seeding operations in the two years separately. One reason is that the method of seeding was changed: it is possible that the method used in the second year was more (or less) effective than that used in the first year of operations, at least for some storm types. Another reason was pointed out earlier. This reason is that we can never be sure that Mr. Vernon's classification of storms into types, especially as modified here, is complete. Presumably, there are more than three distinct classes of storms occuring with frequencies which may vary markedly from one year to the next.

We now present the analysis of the first year's operations, just as it was presented in the spring of 1953 before the data for the year 1951/52 became available. The reader will notice that the authors are cautious in drawing conclusions. We then present the results of the analysis of the 1951/52 operations, and note that the details as to which class of storm was successfully seeded are different in 1951/52 from what they were in 1950/51.

The analysis of the 1950/51 cloud seeding operations. Let us consider the situation from the point of view of the (practically) established fact that the storms that passed over the target in 1950/51 were not all of the same nature but fall into several types as classified by Mr. Vernon. As an

immediate consequence of this, we refrain from identifying with cloud seeding every nonrandom element in the deviations of circles in Figure 11 from the overall regression line and admit the possibility that some of the nonrandomness may reflect the class differences from one storm to the next.

Pursuing this line of thought we identify among the 29 seeded storms shown in Figure 11a the seven units of observation that belong to Mr. Vernon's Class A. These seven units, all of them seeded, are marked with open circles and it will be seen that all of them are well above the overall regression line. In addition, Figure 11a exhibits five crosses. These correspond to five units of observation in 1950/51 that belong to class A and were left unseeded. They are not substantially above the overall regression line. However, as remarked earlier, if the operators had seeded all the storms of class A and refrained from seeding all the others, then an evaluation by the customary regression method would have given a favorable verdict: an increase in the seasonal precipitation by 0.61 inches.

In order to apply the suggested modification of the regression method, we classify all the seeded storms into the three categories of Mr. Vernon, A, B, and C, and plot the precipitation in the target against that in the control separately for each category. This is done in the three panels of Figure 12a which also contains the regression lines of Figure 9, appropriate for each class of storms. The deviation of each point from the corresponding regression line is again a combination of random variation and of some possible nonrandom effects. As was the case with Figure 11a, a statistical test can be used in order to determine whether or not it is safe to assume that any nonrandom effect is present. Also, we may take for granted that a substantial part of the nonrandom effect due to ignoring types, which is present in the deviations in Figure 11a, does not appear in Figure 12a.

The statistical test was actually applied to the deviations in Figure 12a and as a result, we can confidently assert that the data in panels A and B deviate from the corresponding regression lines by more than could be expected from random variation. A similar conclusion can be drawn with respect to class C, although with less confidence in its correctness. The estimated nonrandom change in the seasonal precipitation per rain gage is

seeded storms of class A: increase of 0.47 inches

seeded storms of class B: decrease of 0.76 inches

seeded storms of class C: decrease of 0.14 inches

Totaling these figures we obtain 0.43 inches as the estimated decrease in seasonal precipitation that possibly is ascribable to the seeding of all storms. In the preceding pages the same units of observation were compared with the overall regression line of Figure 11a and this comparison indicated a decrease in precipitation equal to 0.86 inches for the season. The difference between these two estimates, 0.86 - 0.43 = 0.43 inches, represents, then, the effect of the difference between the quinquennium 1945/46-1949/50 and the year 1950/51 in the relative frequencies of storms of different classes that was noted in section 8.

The particular panels of Figure 12a require a closer study. Setting aside the somewhat doubtful effect relating to class C, let us concentrate on the conclusions regarding the other two classes. As mentioned, the seeded storms of class A brought to the target 0.47 inches more rain than could be expected from these storms, judging from the experience of the preceding unseeded quinquennium. It is very unlikely that an excess of this kind could be produced by mere random variation. Is this documentary evidence that the excess in precipitation for class A storms is due to cloud seeding? The answer is an emphatic "No."

The possibility is, of course, that the cloud seeding has no effect whatever but that what we treat as a simple class A of storms is in reality a conglomeration of several subclasses which Mr. Vernon and our own subsequent efforts failed to identify. It is possible that the class A storms of 1950/51 or most of them, belong to a subclass that we may denote by AA, with a regression of rainfall in the target on that in the control much higher than the regression corresponding to the entire class A. This would provide a perfectly satisfactory explanation to what is actually observed in panel A of Figure 12a. Similarly, the undoubtedly nonrandom negative deviations in panel B of Figure 12 a may easily be due not to the detrimental effect of cloud seeding but to the prevalence among the B storms in 1950/51 of storms of some subclass BB.

It will be realized that a similar argument will always apply to the modified regression method, no matter how delicate the classification of the storms. Nevertheless, although we cannot treat the above results as documentary evidence that cloud seeding affects precipitation, we should not lose sight of the fact that an honest effort was made to see whether the classes of Mr. Vernon could be split into finer groups with different regressions and that this effort failed. This suggests that the particular configurations of points in Figure 12a reflect the different effects that seeding has on storms of different classes, beneficial in class A and harmful in class B.

Here it is appropriate to recall that classes A and B were formed a posteriori and that they are composed, one of storms of the subclasses Ia' and Ib' and the other of the subclasses Ic' and IIb. The merging of these two pairs of subclasses appeared justified because of the similarity of their regressions of the rain in the target on that in the control, combined with relative paucity of data. When adopting the combined classes A and B, we cautioned that the similarity of regression need not imply the similarity of the storms in all other respects. Now, faced with the suggestion that the

seeding may have increased the precipitation from A storms and decreased that from B storms, it appears interesting to return to the original classification of Mr. Vernon and examine the behavior of the seeded storms of the component subclasses that were combined into classes A and B. Because of paucity of data, it will be sufficient to exhibit the results for only two subclasses Ia and IIb. They are given in the two panels of Figure 13a.

It is seen that a positive effect of seeding of some storms and a strong negative effect of seeding some others is suggested by the two panels of Figure 13a even more clearly than by panels A and B of Figure 12a. In fact, it is possible that any substantial positive effect of seeding is limited to storms of subclass Ia and that a very strong negative effect applies only to storms of subclass IIb.

As mentioned, the cloud seeding operations in the Carrizo Plain have been carried on during two full seasons, 1950/51 and 1951/52, but, due to the absence of published data on hourly precipitation, the present analysis applies only to 1950/51. It is understood that the publication of these data will be resumed before long and then it will be most interesting to see whether or not the results of the second season confirm the suggestions of the effects of seeding of the different classes of storms noted above. We should not be surprised to find all the interesting tendencies reversed. This would indicate the desirability of a closer meteorological analysis of storms. However, one may hope that the effects suggested by the foregoing analysis of the operations in 1950/51 will be confirmed. In this case the consequences of Mr. Vernon's classification of storms will be very important indeed.

The analysis of the 1951/52 cloud seeding operations in Carrizo. As mentioned, the analysis of the 1950/51 cloud seeding operations in the Carrizo Plain area, as presented in the last five pages, was written in the spring of 1953, before the precipitation data for the succeeding season were available.

The present pages were written after the summer of 1953, when the necessary data had been received and analyzed. We are indebted to Mr. Hugh A. Spangler, Regional Director of the United States Weather Bureau, for enabling us to obtain these data in advance of publication, and to Mrs. M. Vasilevskis, of the Statistical Laboratory of the University of California, who carried out the computations with speed and efficiency.

Unfortunately, many details of the results indicated in 1950/51 operations are not confirmed in the 1951/52 operations. In particular, as indicated in Figure 12b, during the second season the indications are that net effects of seeding of class A were harmful rather than beneficial, whereas they were beneficial instead of harmful for class B. At the same time, the few seeded storms of type C fall below the regression line. Rather surprisingly, even the apparently strong effects exhibited in Figure 13a are not repeated in the next season, shown in Figure 13b. One might guess that at least part of the changes result from changes in the cloud seeding operations themselves.

The estimated effects of seeding are summarized in Table III for each of the two seasons considered separately and then the two combined. This table gives the number of storms of each type during the seeding period (October, 1950 to May, 1951 and October, 1951 to April, 1952), the probability that their regression line is different from the historical regression line (of the quinquennium preceding seeding), the total precipitation from that type of storm (averaged over the four gages in the target area) and the total increase in precipitation (averaged over the four gages). All the information is given twice, first for those storms actually seeded by the operator, and then for all of the storms occuring during the seeding period. Although the details are not the same for the two seasons, the total effect of the cloud-seeding operations is a slight decrease in precipitation for each season.

Table III

WAS SEEDING EFFECTIVE IN CARRIZO?

	1950/51 Season Types				1951/52 Season Types				Both Seasons Types			
STORMS ACTUALLY SEEDED	A	B	C	Total	A	B	C	Total	A	B	C	Total
Number of storms studied	7	14	8	29	7	22	4	33	14	36	12	62
Probability of difference	.92	.98	ns		ns	ns	.94		ns	ns	.95	
Total precipitation (per gage)	1.02	1.20	0.80	3.02	0.54	5.38	0.29	6.21	1.56	6.58	1.09	9.23
Total Increase (per gage)	+0.47	-0.76	-0.14	-0.43	-0.26	+0.62	-0.42	-0.06	+0.21	-0.14	-0.56	-0.49
ALL STORMS IN PERIOD												
Number of storms studied	12	20	12	44	16	30	8	54	28	50	20	98
Probability of difference	.92	.98	ns		ns	ns	.91		ns	ns	.88	
Total precipitation (per gage)	1.08	1.39	0.81	3.28	1.34	6.32	0.35	8.01	2.42	7.71	1.16	11.29
Total Increase (per gage)	+0.40	-0.81	-0.22	-0.63	-0.29	+1.10	-0.49	+0.32	+0.11	+0.29	-0.71	-0.31

Note: ns indicates "no significant difference."

It should be realized that the above analyses of the Carrizo Plain operations are presented not only for their own sakes but also in order to illustrate the working of the suggested modification of the regression method. Now it may be appropriate to point out the advantages. Originally, the modification was suggested as a means of eliminating the confusing effect of different types of storms, the frequencies of which vary from one year to the next. In addition, if it is true that cloud seeding increases precipitation from some types of storms and decreases from some others, then the suggested modification of the regression method will eventually bring this fact out.

The method described here has been applied to two other sections of California, namely Southern Sierra and Santa Barbara County, in which extensive cloud-seeding operations have been performed. For both of these sections also, a classification of storms according to type was established on a meteorological basis (and thus the typing system is somewhat different from that employed in the Carrizo Plain area). The particular classes of storms were found to have significantly different regression lines. Then the precipitation from seeded storms was compared with that predicted by the historical modified regression lines, in the same way as that used in the Carrizo analyses. In these other two areas, the total effect due to cloud seeding indicated some increase in precipitation, which is in contrast with what seems to occur in Carrizo. However, as we have emphasized, none of these analyses present documentary evidence for or against the effectiveness of cloud-seeding. The details of the Southern Sierra and Santa Barbara analyses are published elsewhere in this bulletin.

10. Problem of documentary evidence regarding the effectiveness of cloud seeding. In the preceding sections we have emphasized that the regression method, in its original form and also in the modified form suggested in the present paper, cannot give documentary evidence of the effectiveness of

commercial cloud seeding. At best, as illustrated in section 9, the modified regression method may bring out suggestions as to what the real effect of cloud seeding may be. While on occasion these suggestions may be very valuable, there will always remain the problem of confirming or refuting them, in order to settle the basic question as to the effect of cloud seeding. At the end of section 9 we visualized the possibility that the analysis of cloud seeding operations carried out in the Carrizo Plain area after 1950/51 may confirm the conclusions suggested by our analysis of the figures relating to 1950/51. It will be realized that, although capable of influencing our emotions very strongly, such confirmation will always lack the strength of documentary evidence, because the similarity of conclusions drawn for 1950/51 with those relating to subsequent years may easily be due to the similarity of frequencies of storms of various classes that thus far have not been identified.

The question, then, arises as to whether or not it is at all possible to obtain irrefutable evidence that commercial cloud seeding affects the precipitation in one way or another. In this connection one is led to think of other classes of phenomena of the methods that served to establish the effect of the various relevant factors. Frequently, these methods consisted of laboratory experiments. If the influence of a factor X on a characteristic Y of a phenomenon is studied, and if it is known, at least vaguely, that Y may also depend on some other factors Z, then the physicist will probably do his utmost to arrange that in the course of his laboratory experiment the value of Z be kept constant (at one or, possibly, at several different levels) while the values of X are changed. Then the changes of the values of Y accompanying those of X characterize the studied effect.

The problem of keeping the value of Z constant is frequently troublesome even in a laboratory. Furthermore, there is always the question of whether a given definition of Z involves all the relevant factors that influence Y in

addition to X. Nevertheless, these difficulties have been successfully overcome on many occasions as witnessed by the tremendous progress of the experimental sciences.

In relation to the problem of cloud seeding the symbol Y must be interpreted as the amount of precipitation in the target, whereas X may be treated as being capable of having one of only two "values": x_1 = there is no cloud seeding and x_2 = the clouds are seeded by a specified method. All this is very simple, but there are great difficulties concerning Z. The definition of Z should embrace all the factors that may conceivably influence the effect of X on Y. It is obvious that Z must involve such factors as those used by Mr. Vernon in his classification, and more. Thus, at the present moment, we have but a very indistinct idea of the definition of Z. Furthermore, it must be obvious that the circumstances of any laboratory experiment seeding water vapor in which a substantial number of factors involved in Z are kept reasonably constant, will be so different from what actually happens when real clouds are seeded in the open atmosphere, that the results of such experiment will not be directly applicable to commercial cloud seeding. All that such laboratory experiment can yield is suggestions regarding the machinery of the phenomena in the atmosphere. Those suggestions may be very valuable, but they will require independent confirmation.

The above remarks are meant to emphasize the fact that, when we are concerned with seeding real clouds, not in an isolated chamber but in the open atmosphere, we have to struggle not only with the difficulty of defining Z but also with the fact that there is no possibility of stabilizing any single element that may be involved in Z and affect the precipitation Y. Not only can we not hold constant any one factor that causes the precipitation of the unseeded rainfall to be large or small, but we must take it for granted that in the succeeding storms of a few seasons, over which a reasonable experiment may

extend, the combinations of all such relevant factors will be different. *
It follows that, if experimental evidence regarding the effectiveness of cloud seeding is at all possible, then the nature of the experiments that may yield such evidence must be of a kind essentially different from that developed by the generations of physicists working in the laboratories.

The road to the new kind of experimentation that is capable of yielding documentary evidence in situations like that with cloud seeding has been opened by the memorable work of R. A. Fisher (3). Originally, Fisher's study of the theory of experimentation was mainly concerned with agricultural research where the experiments are made on living organisms, plants or animals, in which the uncontrollable individual differences defied stabilization to a striking degree. Later on, however, a closer scrutiny of the circumstances of physical laboratory experiments revealed that there too a real stabilization of non-experimental factors is more of a myth than a reality and, at the present moment, the experimental techniques developed by Fisher and his school have spread over a great number of domains. The main fruitful idea underlying all these techniques is very simple. It is that, the units of observation to which the experimental factor or treatment is to be applied, must be selected at random. Hence, experiments of this kind came to be described as randomized experiments.

In relation to cloud seeding the randomization means simply that roughly one-half of the units of observation found to be suitable for seeding should be left unseeded and that the units to be seeded should be selected at random. This randomness may be achieved by tossing a coin. However, since most coins

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*In this connection, I wish to quote the opinion, once expressed in conversation by Professor Jacob Bjerknes, that each storm is an independent organism, different from all others.

are slightly biased and since the outcome of a toss depends very much on the method of tossing, it is preferable to use special tables of so called "random numbers" that were compiled and published for this particular purpose (4,5,6). The working of the method is based on known laws of chance and can easily be explained with reference to the evaluation of the Carrizo Plain operations given in section 9.

As discussed in detail in that section, the uncertainty of the conclusions regarding the effects of cloud seeding originates from the uncertainty that the storms, say of class A, observed in 1950/51 and seeded, are identical in nature with the storms observed in the preceding quinquennium that also were labeled A. Now, assume that what Mr. Vernon calls class A of storms is actually a conglomeration of several subclasses with different properties and that the frequencies of storms of these subclasses vary from year to year. If not all of these storms are seeded but only those for which the tossed coin falls heads, then, whatever be the order in which the storms of the particular subclasses follow each other, the known laws of chance guarantee that, with a sufficiently long series of observations, each subclass will be divided in two approximately equal parts, with roughly one-half of all the storms seeded and the other half left unseeded. Then, in the process of evaluating the results of the experiment, a statistical test will determine whether or not the difference in the precipitation from seeded and unseeded storms is large enough compared to the variation from storm to storm in order to warrant the conclusion that, on the average, the seeding of storms of the particular class is effective.

It will be noticed that in the above procedure the observations over the years before seeding do not enter at all and the crucial comparison is based on the storms of the current year, a randomly selected group of which is actually seeded. Nevertheless, even with a randomized experiment, the

observations of the years preceding the randomized cloud seeding experiment can be used in the evaluation in order to construct a more sensitive test. For example, the evaluation may be based not on the totals of precipitation that the particular storms deposit on the target but on the deviations of these totals from the appropriate regression lines discussed in section 9. To illustrate this procedure, imagine that the weather modification company operating in the Carrizo Plain area in 1950/51 and 1951/52 used a random procedure (a coin) to select the storms to be seeded. In other words, assume that out of the 42 + 54 = 96 units of observation (see Table III) the tossing of the coin indicated 29 + 33 = 62 units be seeded and the remaining 34 units be left unseeded (such an unequal division, 62 against 34, may happen by chance from time to time; however, cases of this sort occur but very rarely).

In order to evaluate the experiment separately for each class we compute the average deviation per storm of the actual precipitation in the target from the expected, computed from the regression line. This is done separately for the seeded and for the unseeded storms. The results are given in Table IV.

Table IV

Average deviation from the expected precipitation per gage per unit of observation, Carrizo Plain, 1950/51 and 1951/52

Category	Seeded		Other		Seeded-Other	
	1950/51	51/52	50/51	51/52	50/51	51/52
A	+.07	-.04	-.01	.00	+.08	-.04
B	-.05	+.03	-.01	+.06	-.04	-.03
C	-.02	-.11	-.02	-.02	.00	-.09

The actual number of storms on which the above calculations are based is too small to risk the assertion that the differences in the last columns

reflect the effect of seeding. However, if the number of observations were larger, the last columns of Table V would indicate that cloud seeding was beneficial in the first year and harmful in the second year for storms of class A, was harmful for storms of class B in both years, and had no effect on class C for the year 1950/51 but was harmful in 1951/52. The analysis as to why this should be so belongs to the realm of meteorology.

Although already mentioned above, the authors wish to emphasize that the conclusions suggested by Table IV are purely hypothetical. They are based on the hypothesis that the storms were selected for seeding by tossing a coin and not on some considerations regarding their meteorological nature. This hypothesis is most probably false, and, therefore, no significance should be attached to Table IV which serves solely for illustration.

The problems of evaluating a randomized experiment, of the number of observations needed to have a reasonable chance of detecting the effect of seeding if it exists and is substantial, are not dealt with in this paper. Since the question of whether or not commercial cloud seeding increases precipitation is of growing importance, and since the organization of a proper experiment capable of producing the necessary evidence is simple and inexpensive, the authors wish to conclude the present publication by suggesting that an experiment be incorporated into the cloud seeding operations that now are going on practically all over the country.

The greater part of the expense would go into installing and keeping in operation a reasonable number of recording rain gages, both in the target and in the surrounding areas that may serve as a control. Naturally, the number of rain gages must be adjusted to the size of the target. Also, they should be distributed over the target with reasonable uniformity. Otherwise, the rainfall recorded may have little relation to what actually fell in the most important region. Since this point seem trivial, it is interesting to mention

that the three recording rain gages at Taft, Lost Hills, Cholame, on which the Carrizo Plain operations may be evaluated, strictly speaking, are not located in the Carrizo Plain itself but only on its edges. For this particular target the authors would recommend perhaps a dozen recording gages, uniformly distributed.

Although the above suggestion is made in connection with the proposed randomized experiment, it should be obvious that without relevant records of rainfall, no evaluation of seeding operations is possible. Therefore, the above item of expense should not be considered as pertaining to the proposed experiment.

In order to incorporate a randomized experiment into the program of cloud seeding operations, a particular clause would be necessary in the contract between the weather modification company and the consumers. This clause should specify that the company shall watch for weather conditions which, in the opinion of the company, are suitable for seeding clouds and shall be ready to commence operations at the shortest possible notice. Just as soon as the company decides that a suitable opportunity for seeding is there, the company shall report this fact to the designated representative of the consumers. Thereafter, the company shall either begin operations or abstain from them, according to the indications of the designated representative of the consumers.

With a clause of the above kind, the reliability of the experiment will depend on the consumers. It is suggested that the orders to the company whether to seed or not to seed the given storm be based, most meticulously, on the outcome of a random experiment. As was the case in other domains at the early stages of the introduction of randomization, we anticipate considerable emotional difficulties. For example, it is likely that the representative of a rain thirsty community will find it emotionally difficult to obey the coin if this coin orders not to seed two or three storms in succession. But what will

be the emotions of this representative if the same order comes for the fourth time! Such cases may and, in fact, will occur from time to time and, if it is desired to obtain real evidence regarding the crucial question of the effectiveness of seeding, our suggestion is to rely on the laws of chance and to obey the coin. However, we repeat that the word "coin" should be taken figuratively and that the use of the random number tables is preferable.

In the above connection it is appropriate to mention two other items of cost connected with the experiment. One is the expense in terms of inconvenience. An opportunity for seeding of clouds may well occur at night and the representative of the consumers may be raised from his bed in order to decide whether to seed the clouds or not. Another item that may be considered as one of cost is that of the loss of opportunities for seeding clouds. However, it must be realized that this item of cost is rather hypothetical and may actually turn out to be one of profit. Thus, for example, the above evaluation of the Carrizo Plain operations, tentative as it is, suggests that the seeding of 36 storms out of the 50 available storms of class B, fourteen storms actually produced a substantial decrease in precipitation over the target. It is possible, therefore, that in letting a few of these storms pass by unseeded, the farmers in the Carrizo Plain would have obtained some rain that was dissipated by the seeders. However this may be, the most important argument in favor of losing about fifty percent of opportunities for seeding, on condition that they be selected at random, is that by doing so one could obtain invaluable information for the future, whether to finance the cloud seeding operations at all, whether to seed only storms of class A and not of class B, etc.

References

(1) J. Neyman: "Methodology of statistical evaluation of rain making operations." A mimeographed report to the Division of Water Resources, Department of Public Works, State of California, December 15, 1951.

(2) G. W. Brier and I. Enger: "An analysis of the results of the 1951 cloud seeding operations in Central Arizona." Bull. Amer. Meteo. Soc., Vol. 33 (1952), pp. 208-210.

(3) R. A. Fisher: "The design of experiments." Oliver and Boyd, London, 1947.

(4) L. H. C. Tippett: "Random sampling numbers." Tracts for computers, No. XV, The University Press, Cambridge, England, 1927.

(5) R. A. Fisher and Frank Yates: "Statistical tables for biological, agricultural and medical research." Oliver and Boyd, London, 1938.

(6) M. G. Kendall and B. Babington Smith: "Tables of random sampling numbers." Tracts for computers, No. XXIV. The University Press, Cambridge, England, 1939.

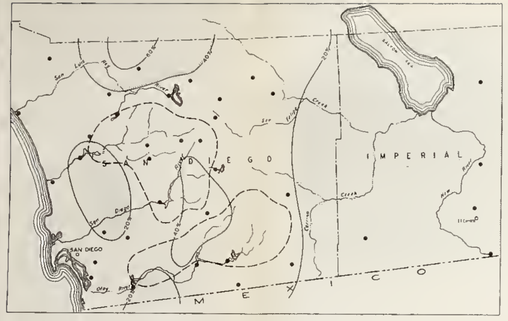

FIG 1 LINES OF EQUAL PERCENTAGE OF NORMAL MARCH PRECIPITATION, FOR SEEDED STORM MARCH 1-2, 1951

LEGEND
AREA WHERE CLOUD SEEDING WAS CLAIMED EFFECTIVE IN INCREASING PRECIPITATION
SEEDING INEFFECTIVE
TARGET AREA
RAIN GAGE

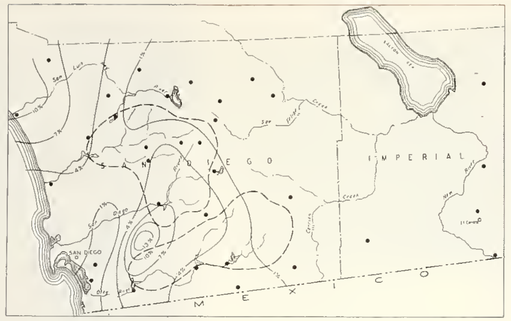

FIG 2 LINES OF EQUAL PERCENTAGE OF NORMAL FEBRUARY PRECIPITATION, FOR SEEDED STORM FEB 16, 1951

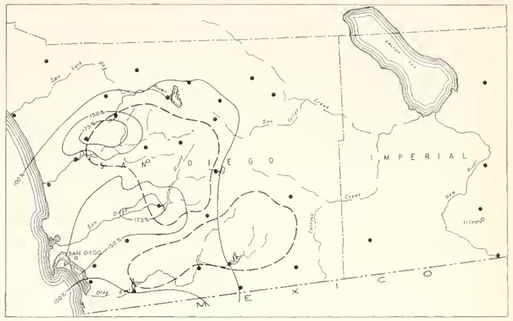

FIG 3 LINES OF EQUAL PERCENTAGE OF NORMAL FEBRUARY PRECIPITATION, FOR UNSEEDED STORM FEB. 12-22, 1950

FIG 4 LOCATION OF TARGET AREA, CONTROL AREAS, AND GENERATORS IN RECENT CLOUD SEEDING OPERATIONS IN SOUTH COASTAL AREA OF CALIFORNIA

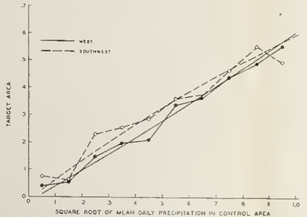

FIG. 5 EFFECT OF WIND DIRECTION AT 10,000 FT. AT 2 A.M. ON REGRESSION

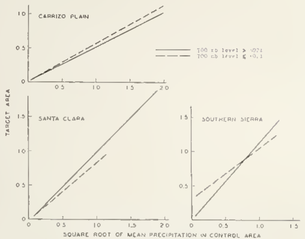

FIG. 6 EFFECT OF STORM TYPE ON REGRESSION LINES FOR THREE DIFFERENT AREAS IN CALIFORNIA

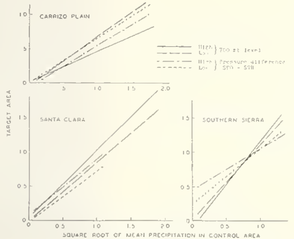

FIG. 7 EFFECT OF STORM TYPE ON REGRESSION LINES FOR THREE DIFFERENT AREAS IN CALIFORNIA

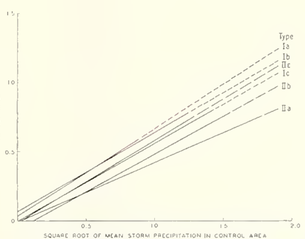

FIG. 8 EFFECT OF STORM TYPE ON REGRESSION, CARRIZO PLAIN, UNSEEDED STORMS, JAN.1945-SEPT.1950, FIRST CLASSIFICATION BY E.M. VERNON

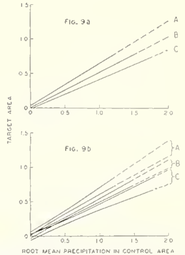

FIG. 9 EFFECT OF STORM TYPE ON REGRESSION, CARRIZO PLAIN, UNSEEDED STORMS, JAN.1945-SEPT.1950, THIRD CLASSIFICATION BY E.M. VERNON

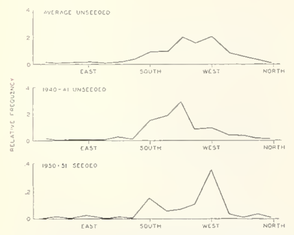

FIG. 10 DISTRIBUTION OF WIND DIRECTIONS ON RAINY DAYS - CARRIZO PLAIN

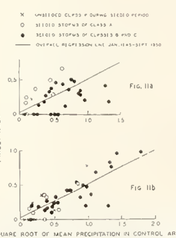
X UNSEEDED CLASS II DURING SEEDED PERIOD
O SEEDED STORMS OF CLASS A
SEEDED STORMS OF CLASSES B AND C
OVERALL REGRESSION LINE JAN. 1945-SEPT. 1950
FIG. IIa
FIG. IIb
TARGET AREA
SQUARE ROOT OF MEAN PRECIPITATION IN CONTROL AREA

FIG 11 CUSTOMARY REGRESSION METHOD APPLIED TO CARRIZO PLAIN CLOUD SEEDING OPERATIONS OF 1950-51 AND 1951-52

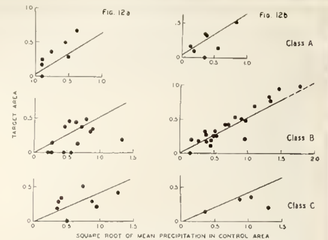

FIG. 12 MODIFIED REGRESSION METHOD APPLIED TO CARRIZO PLAIN CLOUD SEEDING OPERATIONS OF 1950-51 AND 1951-52

● ACTUALLY SEEDED STORMS
MODIFIED REGRESSION LINES

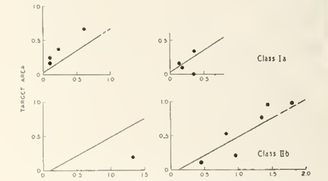

FIG. 13 MODIFIED REGRESSION METHOD APPLIED TO MR. VERNON'S ORIGINAL STORM CLASSES, CARRIZO PLAIN, 1950-51 AND 1951-52

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

FIGURES FOR APPENDIX C

APPENDIX D

EVALUATION OF
WEATHER MODIFICATION OPERATIONS
OF THE SOUTHERN SIERRA PROJECT

A Report to the Division of Water Resources,
Department of Public Works,
State of California,
on Work Performed at the
Statistical Laboratory, University of California
Berkeley, California

This report was prepared with partial
support from the Office of Naval Research

By Arnold Court
Statistical Laboratory
University of California
Berkeley, California

October, 1953

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WEATHER MODIFICATION OPERATIONS
OF THE SOUTHERN SIERRA PROJECT

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FIGURES

(All figures follow page 145)

1. Location of Target Area, Control Areas, and Precipitation Stations, Southern Sierra Project

2. Comparison of Average Storm Rainfall in Southern Sierra Area With Corresponding Value for Yosemite Park Area

3. Simultaneous 50 Per Cent Confidence Intervals for Three Storm Types of Southern Sierra Project

4. Comparison of Storms During Seeded Period With Historical Regressions, Southern Sierra Project

EVALUATION OF WEATHER MODIFICATION OPERATIONS OF THE SOUTHERN SIERRA PROJECT

By Arnold Court

Statistical Laboratory

University of California, Berkeley

1. Introduction

1.1 General. Weather modification was undertaken during the seasons of 1950-51 and 1951-52 over an area of some 2,200 square miles on the western slopes of the southernmost portion of the Sierra Nevada. The operations were sponsored by the Southern Sierra Corporation of Porterville, and conducted by the Precipitation Control Co. of Phoenix, Arizona.

Aircraft based at Kern County Airport, Bakersfield, were used to spread smoke containing silver iodide, sulfur trioxide, or both, in suitable concentrations and along paths and at altitudes judged best on each occasion. The same aircraft were used also for similar operations in a somewhat larger area to the west, on both sides of the Temblor Mountains and including the Carrizo Plain.

Results of the Carrizo operations have already been discussed (Appendix C); the present report is a continuation of that study. It was undertaken largely to determine whether the same techniques of analysis were equally applicable to the Southern Sierra.

No complete study of the Southern Sierra operation was attempted; rather, this is a report on exploration of possible methods of analysis. It was conducted by the Statistical Laboratory of the University of California, under contract to the State Division of Water Resources. The contract was not for evaluations as such, but for investigations of existing methods of evaluation, and development of better ones if possible.

1.2. Area. The area involved in the second season (1951-52) of work for the Southern Sierra Corporation was described by the operator, in his legal notice dated 23 November, 1951, as:

> "from Bakersfield to Tulare bounded on the west by U.S. highway 99, thence Tulare east to approximately Mineral King, thence due south along the Sierras to the Kern River approximately 20 miles east of Bakersfield, thence west along the Kern River to Bakersfield to the point of beginning."

Maps submitted by the operator as part of his official report, however, show a somewhat smaller target area. Here the western boundary is a straight line east of the highway, and the northern boundary lies about 5 miles south of that in the written description. Since the state law requiring prior notice of weather modification operations was not effective until the first season (1950-51) had ended, no public statement was made describing the target area before those operations began. In the absence of any such statement, since sponsor, operator, and method of operation were the same in both years, the target in both is assumed to be that given in the written announcement. The two seasons of operation have been combined for analysis. The area is shown on Figure 1.

In the first season, 43 flights totaling 100 hours were made on 25 days between 13 Nov. 1950 and 30 Apr. 1951, for an average of 2 1/3 hours per flight or 4 hours per day. In the second season, 37 flights totaling 105 hours were made on 20 days between 15 Nov. 1951 and 7 Mar. 1952, for an average of almost 3 hours per flight or 5 1/4 hours per day. In addition, two preliminary flights totaling 7 2/3 hours were made on 24 and 25 Oct. 1951, but the operator's analysis implies they may have been over an area somewhat to the west of the target as later described.

1.3. Purpose. While the area of operations is defined, the purpose is not. The notice of intention concerns merely "a program of weather modification." Presumably, the purpose was to increase the total amount of precipitation in the indicated target area. However, certain other operators have claimed, after operation ended, no increased precipitation but lower intensity, i.e., increase in the number of days of rain rather than increase in amount. Both of these aspects have been examined.

Furthermore, the operator's declaration does not indicate whether all parts of the 2,200-square-mile target area were considered equally important. Almost one half of the area is comprised by the east side of the floor of the San Joaquin Valley, from Bakersfield to Lindsay (about 60 miles), and from U.S. highway 99 (and the paralleling Southern Pacific Railroad) to the Sierra foothills (generally 20 to 25 miles). The only Weather Bureau raingage within this area, at Porterville, indicates an average annual rainfall of about 10 inches; that at Bakersfield, at the southwest corner, shows 7 inches; that at Lindsay, on the north border, 11 inches.

The other half of the area is formed by the western slopes of the Sierra. These rise from the valley floor around 500 feet above sea level to a ridge with crests at 7,000 to 10,000 feet. Annual precipitation here ranges from 20 to 37 inches at the existing gages, and may be higher in some favored localities. Since the description of the target area carefully excludes the north-south valley of the upper Kern River east of the first crest, the major purpose of the operation is taken to have been an increase in precipitation in the drainage basins of the several short streams flowing westward out of the Sierra. These are chiefly the Tule River, Deer Creek, White River, and Poso Creek.

2. Data.

2.1. Target. Precipitation measurements are reported by the U.S. Weather Bureau for only seven places in the 2,200-square-mile target area. One is Porterville, already mentioned, where records have been obtained, with very few breaks, since 1889. On the assumption that increasing Valley rainfall was not the primary purpose of the operation, Porterville data have been used very little in the present analysis.

Of the other six raingages, two are non-recording, at the Glennville Fire Station (since 1950 only) and at Springville Tule Head Dam. Established in 1907 (and called Daunt until 1912) at a powerhouse dam on the upper Tule River, this latter station apparently has had its gage in the same location ever since. Its elevation is 4,080 feet. It has been read faithfully every afternoon by a long succession of electric company employes--or their wives.

Springville Tule thus provides the only long record of precipitation at one location in the entire Southern Sierra target area. Although it is near the northeastern corner, it is well inside the boundaries. It is at the confluence of two branches of the most important stream, the Tule River. It has been used for certain aspects of the analysis.

The remaining four precipitation records are from recording gages, whose charts are evaluated to show the catch during each hour. Their present names are Camp Wishon, Springville Ranger Station, California Hot Springs, and Glennville Fulton Ranger Station. All four were installed in March, 1940, and three have remained in virtually the same locations ever since.

At California Hot Springs, however, the gage was installed at the U. S. Forest Service Ranger station. After almost four years it was moved 1 1/2 miles northeast to the ranch of T. B. Houghton. Five years later, on 13 Oct. 1949, it was moved back to the original location. In this mountainous region, local variations in precipitation are large, but there is no valid way of determining whether these two particular sites differ very much. Consequently, the California Hot Springs record has been considered as homogeneous, and the changes ignored.

Unfortunately, during the war years two of the recording gages operated rather sporadically, and only since March 1946 are records from all four available most of the time. Even during the last six seasons, each of the four has failed to yield records at various times, for differing reasons. Comparison of the periods in which all four operated simultaneously with those during which at least

one was lacking indicates that the periods of joint operation from a fair sample of the total period.

It would have been possible to analyze the records of each gage separately, to determine whether its catch was increased during the two seasons of weather modification attempts. This procedure would permit use of more data, and provide answers for each of the four locations. However, it was assumed that the variability of the average of all four gages would be less than that of the readings of any individual gage, and thus that greater precision in analysis would be attained by using only the averages.

2.2. Controls. Selection of stations whose rainfall could be compared with that of the Southern Sierra target area required consideration, first, of other weather modification operations. The same operator was using the same methods, during the same period, in a large area 50 to 200 miles to the west. At various times other operators had been active to the north, along the Kings and San Joaquin Rivers. Still others had operated along the eastern side of the Sierras in the Bishop Creek area, and to the south in the Antelope Valley extension of the Mojave Desert.

Eventually, two groups of comparison stations were chosen. One group is in, and to the west of, Yosemite National Park, about 100 miles to the north-northwest of the Southern Sierra target. The other is on the west side of the San Joaquin Valley, northwest of Fresno. So far as could be determined, both were free of any other attempts at weather modification. The areas are shown on Fig.1.

Both groups were used in the preliminary analysis, but only the Yosemite group was used for the final comparison. The Yosemite

stations include four recording raingages and five non-recording ones. Elevations of the recording gages are closely comparable to those of the target group:

Yosemite Stations	Elev.	Southern Sierra Stations	Elev.
Wawona Ranger Station	4,100		
Yosemite Park	3,985	Camp Wishon	3,800
		California Hot Springs	3,300
Groveland No. 2	2,825	Glennville Fulton Ranger Stn.	2,975
Cathay Bull Run Ranch	1,425	Springville Ranger Station	1,050

These gages were installed in 1940 or 1941, and three of them remained at virtually their initial locations throughout the period studied. The fourth, Groveland No. 2, was moved .2 mile south in September 1941, then .1 mile west in October 1949, and .2 mile northeast in October 1950. The Wawona gage was moved away during September and October 1941, but returned to within 30 feet of its original location before the rainy season started, and not moved thereafter. The Yosemite gage was moved 50 feet north in August 1942, and not thereafter. The Cathay gage has remained at its original site.

The Valley group had six non-recording gages and three recording gages. Their records were used only to define "storms," as explained below. Locations of gages are shown on Figure 1.

2.3. Storms. Daily rainfall amounts at all 25 stations (7 Target, 9 Yosemite, 9 Valley) were tabulated from July 1941 through June 1952. For the recording gages, for which publication of data was suspended by the Weather Bureau in October 1951, photo-

stats of manuscript tabulations of hourly amounts for the final season were obtained by the Division of Water Resources from the Weather Bureau.

These daily amounts were grouped into "storms" of one to four days, occasionally five or six days. A minimum storm involved precipitation at each of three locations divided among at least two of the three areas. For this purpose, adjacent gages were considered as a single location. Such adjacent gages are Camp Wishon and Springville, Tule, Yosemite Park recorder and non-recorder; Groveland 1 (daily) and 2 (recorder); Merced 1 (daily) and 2 (recorder); and Mendota Dam (daily) and 1 NNW (recorder).

In many cases, several consecutive days with precipitation were divided into two or more storms, from the evidence of the hourly readings. Occasionally, accumulated amounts for several days were shown for one or more gages. Such accumulations arise from one of two causes. One is the stoppage of the clock, due to breakage or lack of attention, and usually affects only one gage at a time. The other is accumulation of snow which does not melt as fast as it falls, but continues to drop into the gage for several days; such conditions often occur at several gages simultaneously, and are the chief cause of long "storm" periods in this analysis.

The number of such storms varied surprisingly little from year to year (Table I). In 10 of the 11 years, the number was between 37 and 43, but in 1949-50 there were only 28. This deficiency, reflecting the very low precipitation of that year, may have helped initiate the modification efforts during the following seasons.

2.4. Types. Four storm types were identified in these data by Mr. Edward Vernon, supervising forecaster at the San Francisco airport station of the Weather Bureau and a consultant to the Division of Water Resources (Appendix F). Because he required oceanic and upper air data for his classification, he studied primarily the storms after January 1945, when such data became available. In addition, he concentrated on the synoptic situation during the 158 storms during the winter half-year, November through April.

Storms were defined as northerly when the wind at 6,000 to 10,000 feet over Santa Maria (about 100 miles southwest of the target area) was northerly (WNW-N-E), at the time of precipitation, and as westerly when the wind was southerly (ESE-S-W). Each type was subdivided into strong and weakening, according to the sea level pressures at Point Arguello and at a spot in the Pacific Ocean about 650 miles to the northwest (see addendum of May, 1953, to Appendix F).

These criteria were designed to distinguish storms which would be expected to give relatively more precipitation to the Yosemite Park area than to the Southern Sierra from others expected, on meteorological grounds, to have the opposite effect. Similar criteria were developed by Mr. Vernon for a proposed comparison of the Valley area with the Southern Sierra, but were not used in this exploratory study, for lack of time.

The classification as submitted by Mr. Vernon deliberately omitted northerly storms for which the Point Arguello pressure was exactly 1019 millibars "in order to omit borderline cases." Application of the classification revealed several such cases, which were tentatively called Type V.

The original identification of storms was based on precipitation at each of three locations divided among at least two of the three areas. In comparing only two of the areas, there were a few storms which gave some precipitation to the Valley area but affected only one station in the Yosemite or Southern Sierra areas, and none in the other. These 5 cases between January 1945 and April 1950 were omitted.

All storms from January 1945 onward (omitting the 5 just mentioned) were classified into the five types. But only 64 percent of them could be studied further, since the analysis method chosen required total storm precipitation from each of eight recording raingages, four each in the Southern Sierra and Yosemite Park areas.

The storms for which data were complete were unevenly distributed over the years, but were more uniformly scattered through the months (regardless of year) and even more evenly spread among the five types. Between one-half and three-fourths of all storms of each type could be studied (Table II).

TABLE I

STORMS IDENTIFIED, BY MONTHS, IN SOUTHERN SIERRA

	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	NOV-APR	TOTAL
1941-42	0	1	0	4	3	9	4	4	3	7	4	0	30	39
1942-43	0	1	0	2	4	6	5	5	6	5	2	1	31	37
1943-44	0	0	0	3	3	7	5	8	3	6	3	3	32	41
1944-45	0	0	1	3	4	4	3	5	8	1	6	2	25	37
1945-46	1	2	2	4	6	6	4	6	4	1	2	0	27	38
1946-47	2	0	1	3	5	3	3	4	8	4	3	1	27	37
1947-48	0	0	1	6	4	6	2	4	6	5	4	1	27	39
1948-49	0	0	0	3	4	7	5	7	10	3	4	0	36	43
1949-50	0	1	0	2	1	4	8	3	5	3	1	0	24	28
1950-51	1	0	1	4	5	4	6	8	3	5	4	1	31	42
1951-52	0	0	0	2	4	7	7	6	6	4	1	1	34	38
Totals:	4	5	6	36	43	63	52	60	62	44	34	10	324	419

TABLE II

RATIO OF USABLE TO TOTAL STORMS TYPED

(First number is usable, second is total typed)

	I	II	III	IV	V	ALL	PCT	Untyped
1944-45	0/2	0/2	0/4	0/9	0/0	0/17	0	
1945-46	0/5	1/3	1/9	2/8	0/2	4/27	15	
1946-47	0/2	4/7	10/12	2/3	1/2	17/26	65	1
1947-48	2/2	9/9	10/10	3/3	1/1	25/25	100	2
1948-49	6/6	3/5	10/12	7/9	2/2	28/34	82	2
1949-50	5/5	3/3	12/12	3/3	1/1	24/24	100	
NOV	2/2	5/8	3/6	1/4	0/0	11/20	55	
DEC	2/4	3/4	8/11	5/5	0/0	18/24	75	2
JAN	4/8	0/2	6/8	2/3	1/2	13/23	56	2
FEB	3/4	3/3	6/8	4/11	2/3	18/29	62	
MAR	2/4	6/8	14/20	3/6	1/2	26/40	65	1
APR	0/0	3/4	6/6	2/6	1/1	12/17	71	
TOTAL	13/22	20/29	43/59	17/35	5/8	98/153	64	5
PERCENT	59	69	73	49	62	64		

2.5. Regression. For each of the five types, modified regressions of the rainfall in the Southern Sierra area on that in the Yosemite Park area were computed, employing all usable storms. The rainfall values actually used for these computations were the square roots of the storm averages for each of the two areas. Each such storm average was based on four recording gages.

Square roots were taken to "stabilize" the variances, that is, to make the scatter about the regression line approximately the same

for large rainfalls as for small ones. Such a procedure had been found effective in similar analyses for nearby areas, and appeared equally good here.

As had been expected by Mr. Vernon, westerly types (III and IV) gave relatively more rain to the Southern Sierra area than to the Yosemite Park area, while northerly types (I and II) had the opposite tendency. Also, as had been expected, within each of these directional groups, the stronger type (II and IV) gave relatively more rain to Southern Sierra than its weakening counterpart (I and III). Type V, which was a "borderline case" between Types I and II, fell very close to the average for all 98 storms (Fig. 2).

But the Type II, III, and V regressions were very close together. As a first step in studying these lines, each of the 10 pairs was compared by the standard F-test. The only differences significant at the 90 percent level were I-IV (above 99 percent) and II-IV (above 95 percent).

Accordingly, Types II, III, and V were combined into a single Type VI, for which a new regression line was computed. It was significantly different, using the F-test, from both Types I (above 90 percent) and IV (above 99 percent). Thus the 98 usable storms of the five seasons prior to the period of operation were grouped into three types:

I. Weakening Northerly, favoring Yosemite, 13.

IV. Strong Westerly, favoring Southern Sierra, 17.

VI. Intermediate, favoring neither, 68.

Although the regressions for these three types had been found to be significantly different, pair by pair, it was necessary to determine

that they differed simultaneously. The multi-comparison F-test, designed for the purpose by Dr. T. A. Jeeves of the Statistical Laboratory, was used. Figure 3 shows the simultaneous 50-percent confidence bands for the three regression lines.

Wherever two such bands do not overlap, the probability is at least 50 percent that the corresponding lines are different Type VI is seen to differ from Type IV only when X, the square root of the average precipitation in the Yosemite Park area, exceeds .3, and to differ from Type I only when X is less than 1.0. Types I and IV overlap for X between .1 and 1.7. The Type VI band is much narrower than the others because it is based on four or more times as many observations as either of the others.

Since the bands do not overlap over substantial regions, the test shows that the probability that the all true regressions are actually different (each from all the others) is greater than 50 percent.

3. Analysis

3.1. Comparisons. During the two winter seasons, 1950-51 and 1951-52, of weather modification operations in the Southern Sierra, 65 storms were identified by the criterion used for preceding years. Of these, 51 were usable, in that data were available from each of the eight recording raingages. In addition, a usable 66th storm, of October 24-26, 1951, during which operation also was reported, was included.

Of these 66 storms, 52 were usable. During only 30 of the 66 storms did the operator's log show any weather modification efforts, but 6 of these were not usable. By types, these storms were:

	Operation				No Operation				Both
Types	I	IV	VI	ALL	I	IV	VI	ALL	ALL
Usable	4	6	14	24	4	7	17	28	52
Unusable	0	2	4	6	1	3	4	8	14

Pertinent information on all 66 storms is shown in Table III, including the total minutes of flight operation reported. In cases of consecutive storms separated according to the hourly precipitation figures, operational minutes were assigned by the same method, according to the flight logs.

Only one flight was not credited to a storm. On April 3, 1951, two simultaneous flights totaling 220 minutes were reported between 4:15 and 6:30 p.m., 32 hours before any precipitation was registered at Camp Wishon, the first Southern Sierra gage to show rain. The storm of April 4-7 was thus analyzed as non-operation; however, since the resulting precipitation was only .01 inch more than predicted by the appropriate storm type regression, its transfer to the operation group would not have altered the analysis appreciably.

For each of the three types, two regression lines were computed by the same procedure as for previous years. One line was based on all usable storms during the period. The other was for only those storms during which operation was reported.

Each of these six lines was compared, by the standard F-test, with the line for its type determined for the preceding years. Regression coefficients for each of these nine lines are shown in Table IV. Results of the comparison are summarized in Table V.

TABLE III

STORMS OF OPERATION PERIOD

For each of 66 storms identified from rainfall records are shown dates, the type (T), the total minutes (Min) of flight as reported by operator, the 4-gage average precipitation in the Yosemite Park area (X), the 4-gage average precipitation in the Southern Sierra area (Y), the precipitation expected in Southern Sierra from the given Yosemite average (EY|X) according to the particular type, and the difference of observed minus expected.

Dates	T	Min	X	Y	EY|X	Diff.
NOV. 1950						
13-15	IV	240	.13	1.49	.33	+1.16
16-17	VI		.92	.05	.59	-.54
18-19	VI	195	-	-	-	-
20-21	VI		-	-	-	-
30-1	VI	210	-	-	-	-
DEC. 1950			-	-	-	-
2-4	VI	315	-	-	-	-
5-8	VI		-	-	-	-
13-15	VI	90	1.10	.43	.68	-.25
30-31	IV	105	.16	.28	.36	-.08
JAN. 1951						
3-4	I	90	.20	.00	.10	-.10
10-12	VI	840	1.96	1.35	1.09	+.26
15-17	VI	390	.48	.41	.37	+.04
17-19	VI	540	2.00	1.15	1.11	+.04
21-23	I		.20	.01	.10	-.09
29-31	I	470	.17	.38	.10	+.28
FEB. 1951						
4-5	I		1.16	.16	.44	-.28
10-12	I	645	1.05	.92	.40	+.52
18	I	120	.03	.19	.08	+.11
21-23	VI	270	.26	.11	.26	-.15
23-25	IV		.08	.12	.26	-.14
25-26	VI		.18	.16	.21	-.05
26-28	IV	900	.31	1.13	.51	+.62
28-2	IV		.42	.81	.62	+.19
MAR. 1951						
3-6	I		1.81	.80	.71	+.09
9-10	VI		.04	.02	.13	-.11
29-30	VI		.01	.05	.11	-.06
APR. 1951						
4-7	VI		.04	.14	.13	+.01
19-20	VI		.12	.11	.18	-.07
23-24	IV		.07	.00	.25	-.25
25-27	IV		.17	.50	.36	+.14
27-30	VI	345	2.23	2.52	1.22	+1.30

Dates	T	Min	X	Y	EY|X	Diff.
OCT. 1951						
24-26	VI	460	1.91	1.23	1.06	+ .17
NOV. 1951						
11-12	VI		.49	.00	.38	-.38
19-22	VI	825	4.00	1.77	2.04	-.27
23-24	VI		.06	.03	.14	-.11
26-27	I		.08	.00	.08	-.08
DEC. 1951						
1-2	VI		2.67	1.28	1.42	-.14
3	VI	135	.93	.93	.59	+.34
4-6	VI	330	1.72	1.97	.97	+1.00
12-13	IV	300	.06	.52	.23	+.29
18-20	IV	210	-	-	-	-
25-26	VI		.15	.00	.19	-.19
28-31	VI	1235	-	-	-	-
JAN. 1952						
6-7	IV	220	.78	.38	.94	-.56
7-8	IV		.18	.23	.38	-.15
11-13	VI	465	2.28	.84	1.24	-.40
14-16	VI	490	4.29	2.91	2.17	+.74
17-18	IV		.02	.44	.18	+.26
20-21	VI		.50	.31	.38	-.07
24-26	VI		3.38	2.17	1.75	+.42
FEB. 1952						
1-2	VI		1.23	.83	.74	+.09
11-12	VI	240	1.05	.56	.65	-.09
16-18	VI	360	.80	.57	.53	+.04
20-21	VI		.48	.32	.37	-.05
21-23	VI		.16	.15	.20	-.05
29-2	IV	670	.56	2.01	.75	+1.26
MAR. 1952						
3-4	VI		.13	.23	.18	+.05
6-8	IV	300	-	-	-	-
9-11	IV		-	-	-	-
12-13	I		-	-	-	-
15-17	VI		-	-	-	-
18-20	VI		2.19	.86	1.20	-.34
APR. 1952						
7-8	IV		.71	.57	.89	-.32
9-11	IV		-	-	-	-
12-14	VI		-	-	-	-
25-27	IV		-	-	-	-

Each of the lines appears to indicate more precipitation in the Southern Sierra than was predicted by the lines obtained for previous years. That is, type for type, relatively more precipitation was reported in the target area during the two seasons of weather modification attempts than during previous seasons.

But the probability was more than 1/2 that the increases for all storms of each type during the two seasons, were due to chance alone. When only the operational storms were considered, however, the probabilities that the observed increases were real, and not due to chance, were 85 and 89 percent, respectively, for the four Type I and six Type IV storms, but only 58 percent for the 14 Type VI storms.

TABLE IV

REGRESSION COEFFICIENTS, BY STORM TYPES, OF PRECIPITATION IN SOUTHERN SIERRA ON THAT OF YOSEMITE PARK AREA

$\sqrt{\bar{Y}}$: Square root of average of four Southern Sierra "target" gages.

$\sqrt{\bar{X}}$: Square root of average of four Yosemite Park area gages.

S^2: Sum of squares of departures of n storms from regression line $\sqrt{\bar{Y}} = a + b\sqrt{\bar{X}}$

Type		a	b	S^2	n
I	Antecedent Period:	-.171	.717	.523	13
	Operation Period:	.038	.597	.548	8
	Operation Storms Only:	.137	.712	.281	4
IV	Antecedent Period:	.187	.844	1.073	17
	Operation Period:	.420	.688	1.376	13
	Operation Storms Only:	.818	.208	.627	6
VI	Antecedent Period:	.081	.658	5.667	68
	Operation Period:	.007	.761	1.254	31
	Operation Storms Only:	.078	.750	.531	14

TABLE V

WAS SEEDING EFFECTIVE IN SOUTHERN SIERRA?

November 1950 to April 1951, October 1951 to April 1952

TYPES	I	IV	VI	Total
"STORMS" ACTUALLY SEEDED				
Number of storms studied	4	6	14	24
Prob. of difference	.85	.89	.58	-
Total Pcpn. (avg. per gage)	1.49	5.81	16.74	24.04
Total increase (per gage)	.81	2.68	2.76	6.25
ALL "STORMS" IN PERIOD				
Number of storms studied	8	13	31	52
Prob. of difference	.47	.48	.42	-
Total Pcpn. (avg. per gage)	2.47	8.48	23.45	34.40
Total increase (per gage)	.45	2.41	1.18	4.05

FIG. 1 LOCATION OF TARGET AREA, CONTROL AREAS, AND PRECIPITATION STATIONS, SOUTHERN SIERRA PROJECT

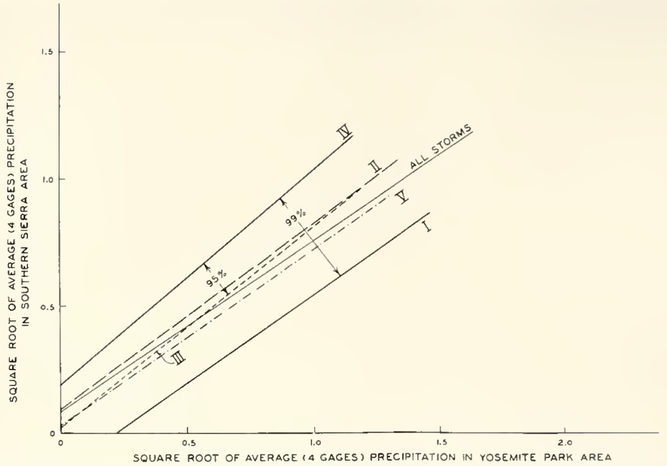

FIG. 2 COMPARISON OF AVERAGE HISTORIC STORM RAINFALL IN SOUTHERN SIERRA AREA WITH CORRESPONDING VALUE FOR YOSEMITE PARK AREA, FOR EACH OF FIVE STORM TYPES

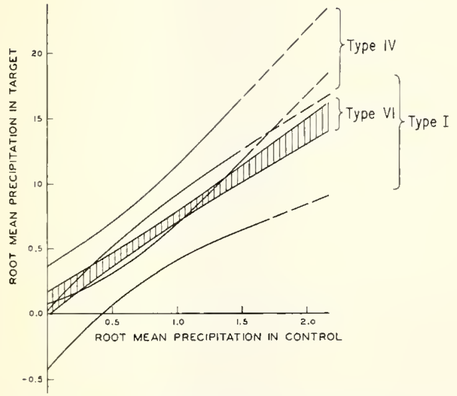

FIG. 3 SIMULTANEOUS 50 % CONFIDENCE INTERVALS FOR THREE STORM TYPES OF SOUTHERN SIERRA PROJECT

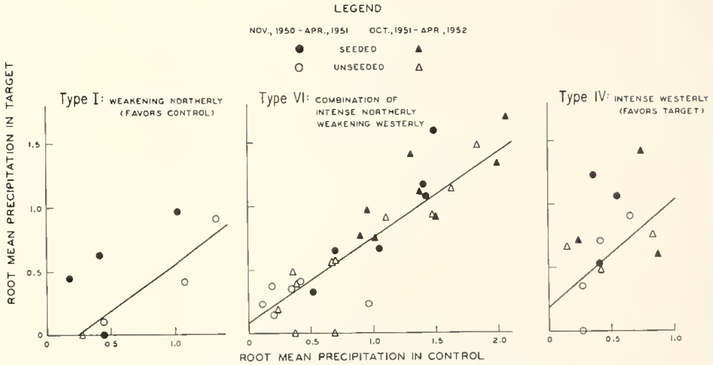

FIG. 4 COMPARISON OF STORMS DURING SEEDED PERIOD WITH HISTORICAL REGRESSIONS, SOUTHERN SIERRA PROJECT

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

FIGURES FOR APPENDIX D

APPENDIX E

SELECTION OF PREDICTORS FOR STATISTICAL FORECASTING OF RAINFALL AMOUNTS IN THE "CARRIZO-TREMBLOR" AREA OF CALIFORNIA

Report to the Division of Water Resources
Department of Public Works
State of California
and to
Professor J. Neyman
Statistical Laboratory, University of California
Berkeley, California

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Professor of Meteorology
Department of Meteorology, University of California
Los Angeles 24, California

May, 1952

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1. Introduction. The present report is written at the request of Mr. R. Reynolds of the Division of Water Resources, Department of Public Works, State of California and Professor J. Neyman of the Statistical Laboratory, University of California, Berkeley, to provide a meteorological basis for an attempt to correlate the total rainfall recorded daily or during each storm in an area west of Bakersfield with weather characteristics observable before the period of rainfall. As a background for this study the weather maps associated with all the rains occurring at stations in this area during a five year period were examined. Also weather maps for a considerable number of days when rain did not occur in this area were studied in order to make sure that the characteristics chosen as representative of the rainy situations were not also representative of the non-rainy situations.

While the weather maps were examined sufficiently to ascertain apparent correlations with the factors suggested below as predictors, no numerical checks on their validity as such were attempted, it being presumed that this numerical work could be done more systematically and thoroughly at the Statistical Laboratory. The basic hypothesis used in arriving at predictors is that the approach to forecasting based on the synoptic weather map is an effective procedure for applying our understanding of the physical processes to problem of prognosis, and that in attempting to choose parameters for use in a statistical substitute for the human integration of the problem, analogous considerations should be applied.

In Section 2 of the report is presented a discussion of the nature of forecasting precipitation, including some comments on the special difficulties involved in forecasting for this area. Section 3 contains a classification of storms producing rain there, designed specifically to facilitate the selection of forecast parameters, or predictors, for each type. Section 4 is

devoted to a discussion of general aspects of the problem of selecting predictors. Section 5 gives the predictors chosen for forecasting the daily rainfall from each type, with further justification for the choice. In Section 6 the problem of use of predictors to forecast total rain for each storm instead of each day is discussed.

2. Precipitation in the "Carrizo-Tremblor" Area.

The area concerned in the study, which is designated the "Carrizo-Tremblor" area, is one of the driest in California. The east portion, in which rain gauges are located at Middlewater, Lost Hills, Taft, and Maricopa, lies in the "rain-shadow" of the coastal mountains and has about five inches average annual precipitation. The portion to the west of the coastal divide, with rain gauges at Cholame Hatch Ranch and La Panza, is also very dry, although the access of the coastal valleys to moisture from the west leads to almost twice as much rainfall at these stations as occurs at the others.

The factors which are responsible for the lightness and infrequency of precipitation in this area make for difficulty in predicting precipitation there. Of the storms (frontal or low pressure systems) which bring rain to the adjacent coastal areas, one-third to one-half do not result in precipitation in the eastern part of the "Carrizo-Tremblor" area. Thus in the five-year period from July 1945 to June 1950 Paso Robles, near the coast, had 195 days with 0.01 inch or more of rain, while Maricopa had 133 and Middlewater 118. The problem of forecasting the extent to which the rain will get over the coastal mountains greatly complicates the prediction of precipitation in this area.

In general, precipitation occurs when moist air moves upward and cools below its condensation temperature. The need for sufficiently thick clouds

and for ice crystal formation will be presumed to be satisfied when the upward motion is adequate in extent and magnitude. In addition to the amount of moisture and of upward motion, the stability of the air, that is, its tendency to favor or resist free convective overturning, will be the principal determinant of the amount and character of the precipitation.

Large scale upward motion in the atmosphere is caused by convergence in the flow patterns, and by ascent over mountains and fronts. In addition to rain caused by such large scale vertical motions, rain occurs in the form of local convective showers induced by heating. Even in the latter case, however, the large scale flow pattern frequently plays a role in favoring formation of showers where convergence is present, or inhibiting them in regions of divergence.

In California the precipitation, confined almost entirely to the winter season, is associated with large scale upward motion, and occurs whenever the flow pattern is such that it brings a deep enough layer of moist air more or less perpendicularly toward mountain ranges. When the air is potentially unstable so that its ascent of the mountains releases free convection as well, the amounts are large. Thus the Weather Bureau Hydrometeorological Report No. 3, "Maximum Possible Precipitation over the Sacramento River Basin" summarizes the synoptic situation for heavy precipitation over that region as follows:

> "The rainfall of flood-producing storms over the Sacramento Basin is released from moist unstable air which originates over the polar regions of the northwest Pacific area, travels southeastward across progressively warmer waters to about the vicinity of the Hawaiian Islands and then northeastward over somewhat cooler waters and onto the continent. Heat and moisture are rapidly added to the air from the sea surface during much of its journey. The instability, produced by the rapid increase in temperature of the air at the surface, results in vertical motions which carry heat and moisture to greater and greater heights. In flood-producing

> storms the height to which this moist unstable layer extends is approximately 10,000 feet before moving inland. In the final stages of its movement toward the coast the air passes over cooler water and becomes stable in a shallow layer next to the sea surface. This stable layer retards release of the potential energy in the moist air until orographic, frontal or isentropic lifting is encountered. As the air is borne inland from the southwest it is acted upon by the unchanging and efficient rain-producing mechanism of the Sacramento Basin's topography. Because the circulation described is impossible with summer pressure distribution the storms are naturally confined to the colder half of the year."

The analysis presented in this quotation applied equally well to the coastal regions and the Sierra slopes throughout California. Wherever the topography is such that the moist air current from the west or southwest is lifted, precipitation will occur. In the down-slope lee of the ranges, however, the precipitation will ordinarily take place only to the extent that the upward air motion induced by the mountains is continued due either to general convergence which offsets the downward tendency normally produced by the mountains, or to extension of upward motions in the lee of the obstacle by wave action (e.g. the "Sierra Wave"). The general convergence is usually associated with low pressure troughs and fronts, and thus ordinarily the very conditions which lead to the impingement of moist unstable air on the coastal mountains (usually the approach of a trough with or without an associated front) will favor the extension of the precipitation to the lee slope.

Perhaps the most favorable circumstance for precipitation at the lee stations of the C-T area would be a case where the low level winds are northeasterly, blowing southwestward up the San Joaquin Valley, while the higher level winds are from the southwest. Short of a clear-cut case like the one just described, it is hard to recognize from the weather map the extent to which the general convergence will permit precipitation to continue in the lee of the mountains. While the forecaster can do quite well in general in determining from the fields of pressure, temperature and moisture at various

levels the extent, duration, and to a lesser degree the amount of precipitation on windward slopes, on the lee slopes he can only make a crude estimate, although he can be sure that if any occurs at all the amounts will almost always be small. Even after the storm has passed the forecaster cannot tell with certainty from the aforementioned fields whether or not precipitation occurred in the area. Thus if the statistical procedures establish predictors with fair to good success, it will be a contribution to the problem of forecasting for such areas.

3. Types of Storms Affecting the "Carrizo-Tremblor" Area.

As a basis for proposing a set of predictors - the rain-producing storms of the period July, 1945 - June, 1950 were studied by the author to determine their characteristics. A wide variety of situations were found to precede the occurrence of precipitation in the C-T area, but there were certain features characteristic of the periods during which the precipitation occurred:

(1) On the sea level map, a low pressure area was moving eastward or southeastward toward Nevada. This LOW in most cases moved from a position over the ocean the day before precipitation began, but in some cases was already on shore over Washington or Oregon. In most of the cases of moderate to heavy precipitation it was south of 45°N latitude 24 hours before the rain began.

(2) On the 500 mb map (characteristic of all upper level maps) there was a trough approaching the coast, with winds with a southerly component over California at the time the precipitation began. In most cases of heavy rain there was a closed low center at 500 mb, off the California coast.

(3) The passage of an occluded or cold front, or in some cases a series of such fronts, was indicated during almost every case of precipitation.

The maps preceding the days with precipitation could be classified

according to the position of the Pacific anticyclone, e.g. west, south, or north of its normal position, but from the standpoint of selecting predictors, this is probably not the best basis. The procedure of forecasting from the synoptic weather maps requires different consideration of the cases where there is a well defined front crossing the coast (to the north of the forecast area) and those in which the front has not yet reached the coast or is absent.

The following classification according to the sea level map is therefore proposed.

I. Well defined front crossing coast of U. S.

A. Low pressure center inland.

B. Low center at coast.

C. Low center still over ocean.

II. No well defined front crossing U. S. Coast

A. Low center over ocean south of 45°N lat.

B. Low center over ocean north of 45°N lat.

(note: cases with two centers, one south of 45°N, grouped with A)

The maps used in the classification were those for 1230 Greenwich Meridian Time (0430 120th Meridian Time) of the date preceding the day the precipitation was recorded. Thus the map time preceded the period of the precipitation as recorded in Climatogical Data of California by 14 to 20 hours. In a few cases the maps did not fall into either of the above types. On January 18, 1949, for instance, no front intersected the coast, nor was there a LOW present off-shore, but precipitation began on the 19th. In this case a low developed practically in situ on a stationary front just off the central California coast. If the 0030 GMT Jan. 19 map had been used for classification, it would have been found to be in Class IIA in advance of the beginning of rain.

4. General Aspects Concerning Selection of Predictors for Precipitation in the "Carrizo-Tremblor" Area.

As discussed in Section 1, the problem of forecasting from the sequence of weather maps the occurrence and amount of precipitation in this area is complicated by its position in the rain shadow of the coastal mountains. In addition to the factors to be considered in forecasting for the coast, it is necessary to consider whether or to what extent the precipitation will carry over to the lee side of the mountains.

In forecasting for the coast the factors to be considered are (1) direction of flow relative to orographic barriers; (2) convergence in flow; (3) availability of moisture; and (4) stability of air. For the coastal region from San Francisco south to Pt. Arguello winds with a westerly component will be directed normal to the land contours, but it is well known that winds north of west rarely accompany rain. The usual pattern is actually easterly or southeasterly wind at the ground, going quickly around to southwesterly flow at all upper levels, in the initial stages of rain. This is because of the requirement that the normal divergence and subsidence of air from the northwest around the eastern end of the anticyclone must be replaced by general convergence in the flow pattern in order that the moisture extend to sufficiently high levels, and the air be sufficient labile to permit the upper layers to participate in the forced ascent. Thus southwest flow, cyclonically curved isobars or isobaric surface contours, and the approach of a front are the conditions for a forecast of coastal rain.

The weather forecaster estimates the time of occurrence of these factors in terms of translation of existing systems on the map with speeds determined from their positions on the preceding maps, together with dynamic considerations concerning changes in speed and development of the systems.

He considers the probable trajectory of the air which will reach the coast, its structure as indicated by radiosonde observations in the places from which it is coming (insofar as these are available) and the modifications (heating or cooling over the sea) to which it will be subjected as it approaches the coast.

In estimating the amount of precipitation at a station, one must take into account the duration as well as the intensity. In the case of the 24 hour amount measured at a particular time of day this means concern with the time of beginning as well as the total duration. A rain beginning late in the 24 hour period would contribute a smaller total than one beginning earlier, provided it did not end in both cases before the end of the period. In the case of the total for a storm, however, the relation of time of observation to the time of occurrence does not enter.

For the predictors of the daily amounts, therefore, we must choose measures which will take account of the timing of the storm; for the predictors of storm totals we must try to find measures of the overall intensity and total duration of the precipitation.

In summary of the above, we must find quantitative measures of (1) the amount and duration of forced ascent to which the air will be subjected (2) the amount and duration of convergence in the general flow, which reinforces the forced ascent and extends it to leeward of the mountains, (3) the moisture supply, and (4) the stability of the air participating in the ascent. For the daily amounts we must also take into account the timing of the storm. Finally we must seek measures of the extent to which the precipitation will extend to the lee of the coastal mountains.

5. Predictors for Forecasting Daily Precipitation in the "Carrizo-Tremblor" Area

The object is to forecast the amount of rainfall during 24 hours beginning 8 a.m. of each day in terms of parameters measured previous to that time. In general these parameters will be obtained from the sea level weather maps of 0430 PST and upper level maps and radiosonde and radiowind observations of 2000 PST (8 p.m.) the previous evening.

We first consider the case where it is not raining in the area at the time of the 0430 PST weather map (as interpreted from the reports at Santa Maria and Bakersfield).

The first question is the proximity of rain-producing conditions, and for this we must use measures of the distance and speed of approaching storms. For distance we choose, in type I storms, the latitude L of intersection of the front with the coast, in type II A the longitude l_A of the low center, and in type II B the longitude l_B of the lowest pressure found along the 40th parallel between the coast and 150°W. If there is no pressure minimum along the 40th parallel between the coast and 150°W in type II B, the forecast is that there will be no rain in the forecast period.

For the speed of approach, in type I the difference P in pressure between the point of intersection of the front with the coast and a point (say) 500 miles seaward along the front should be used. For type II A the difference between the average height of the 500 mb surface at 35°N and at 45°N between the coast and 155°W is indicated. This quantity, called a zonal index, is more explicitly

$$Z = H_{35,125} + H_{35,135} + H_{35,145} + H_{35,155} - H_{45,125} - H_{45,135}$$

$$- H_{45,145} - H_{45,155}$$ where $H_{35,125}$ is the height of the 500 mb surface at 35°N and 125°W, etc. In addition to this quantity, a meridional index

$$M = H_{55,155} + H_{50,155} + H_{45,155} + H_{40,155} - H_{55,140} - H_{50,140} - H_{45,140} - H_{40,140}$$

must be considered in estimating the speed of movement of type II B storms.

The expected relationship between these parameters and the precipitation should be somewhat as follows. The time from the observation of L (or l_A or l_B) to the beginning of precipitation will be $(L-x_1)/kP$ where x_1 is the distance from the station to the front at the time of beginning and k is a factor for converting P (or M or Z) from pressure gradient to speed units. If x_2 is the linear dimension of the rain area associated with the storm, then the total duration of rain is x_2/kP. Let t_o be the time interval from the time of measurement of L to the time of beginning of the 24 hour measurement period. Then the duration of the rain during the 24 hour period is $24 + t_o - (L-x_1)/kP$ or x_2/kP, whichever is smaller. For the same average intensity the 24 hour precipitation R_{24} will be proportional to the smaller of these quantities. If the first is smaller, R_{24} will depend on L, smaller for larger L and the same P; for the same L, R_{24} will vary directly with P, reflecting the fact that for rain lasting until the end of the period, the earlier it starts, the more there will be. If the second of the above quantities is smaller, R_{24} will be independent of L, and vary inversely with P, reflecting the fact that if the rain occurs entirely within the 24 hour period, the faster it moves, the shorter it lasts, and the smaller its total, for the same intensity.

To include consideration of the total duration we must find some measure corresponding to x_2, the equivalent linear dimension of the rain area. Since the storms ordinarily move in from the ocean, where observations are not available for delimiting the rain area, and since the precipitation pattern is modified on reaching the coastal mountains, it is necessary to use some indirect measure of the magnitude of the storm. The extent of the southerly flow aloft might be such a measure, and it is suggested that the longitude

difference d from the ridge to the trough in the 500 mb contours be used. Ordinarily the ridge will be near the coast, either just off shore or just a little inland, and the trough will be between 135°W and 150°W. In some cases the ridge will not be conspicuous, in which case the longitude difference from the coast to the height minimum, say along the 40th parallel, should be used.

This measure of the extent of southerly flow, in so far as it can be evaluated, should also be somewhat correlated with the intensity, since it gives some suggestion of the extent of trajectories from the south, which involve convergence of the general flow pattern and advection of moist air masses. More direct measures of the intensity to be expected would be quantities proportional to the strength of southerly and westerly flow, the former being associated with general convergence, and the latter with the rate of forced ascent over the mountains. For the latter we have already introduced the zonal index Z, which now should be used not only as a speed parameter in type II A, but as a forced ascent parameter in all cases. For the strength of southerly flow an additional meridional index, which we shall call S, should be used, consisting of the difference between the average heights of the 500 mb surface along the 125°W meridian and the 135°W meridian, between 30°N and 45°N.

$$\Delta S = H_{30,125} + H_{35,125} + H_{40,125} + H_{45,125} - H_{30,135} - H_{35,135} - H_{40,135} - H_{45,135}$$

It might be that the 500 mb surface is too high for this purpose, and that the 700 mb or even the 850 mb surface might be better.

Both so far as the moisture supply is concerned and so far as the stability of the air is concerned, we can probably do no better than to take estimates from the radiosonde observation at Santa Maria most nearly preceding the time of beginning of the forecast period. For the moisture it is desirable to take the dew point T_d, at two or three levels, say surface, 850 mb, and

700 mb. If it is desired to reduce them to a single parameter, this can be done by obtaining the corresponding mixing ratios and averaging them. For the stability the temperature differences between 850 and 700 mb, and between 700 and 500 mb seems suited. In this case averaging would be unsuitable, and if a single stability parameter is desired the temperature difference from 850 to 500 mb should be used. The use of the data at Santa Maria makes no allowance for changes in the moisture content and stability during the forecast period. To make such an allowance each situation would have to be considered individually. The zonal and meridional indices to a limited extent will indicate these changes; beyond them no parameters uniformly measured seem likely to do so.

The above parameters to some extent already take account of the factors determining whether and to what extent precipitation will occur on the lee slopes. As an additional indicator, the surface or 2000 ft. wind at Bakersfield (or Fresno) and/or the wind at Sandberg may be used. These winds, or rather the northeast-southwest components of them, reflect the degree that up-valley flow in the San Joaquin will augment the general convergence in favoring upward motion on the east side of the coastal range.

In summary, the following parameters have been suggested:

L, l_A, l_B, distance from "storm".

P, Z, M: pressure gradients indicating speed of movement.

S, Z: pressure gradients indicating convergence and forced ascent.

d: distance indicating dimension of rain producing system.

T_{do}, T_{d8}, T_{d7}: dew point temperatures at Santa Maria at surface, 850 mb, and 700 mb, or

w : average humidity mixing ratio between surface and 700 mb.

T_1, T_2: temperature differences at Santa Maria from 850 to 700 mb and from 700 to 500 mb or

T_3: temperature difference at Santa Maria from 850 to 500 mb.

V_B: Northeast-southwest component of the 2000 ft. wind at Bakersfield or Fresno.

V_S: Northeast-southwest component of the surface wind at Sandberg.

For each type of weather situation there are a maximum of 13 parameters suggested, but use of as few as eight will take some account of all factors discussed. Experience may show that some of these are sufficiently intercorrelated to make unnecessary the use of all of them.

The discussion so far has presumed that the rain has not begun at the time of the forecast. If it has, of course, L, l_A, or l_B, measuring the "distance from storm", is immaterial, and instead there must be substituted some indication of how much of the storm has passed. For this purpose perhaps the best indication might be the length of time since precipitation began at Santa Maria, or, if it is preferred not to use precipitation, the length of time since the pressure began falling.

In its approach to "objective weather forecasting" the Weather Bureau has usually preferred to use data obtained directly from the observations, rather than those coming from analyzed weather maps. In the above we have relied on the analyzed maps a good deal, with the attitude that our purpose was in so far as possible to reflect the procedures by which the synoptic forecaster applies physical principles to the analyzed fields of mass and motion. To reject the analysis as subjective is, it appears to me, to imply that intelligence cannot extend our understanding of these fields beyond the discrete point set at which observations are made. While it is true that at times the analyst may inject into the maps models which, based on incomplete theory, do not correspond to reality, this is overcompensated by the more frequent occasions when physical principles lead to an illuminating correlation of apparently unrelated data.

6. Prediction of Storm Totals.

In order to forecast the total rain for a storm, rather than for a 24 hour period, the consideration of the distance from the storm in terms of the time of beginning of precipitation does not enter. On the other hand, it does give some measure of the probability that the storm will reach the station at all, and thus should be retained as a factor. The other parameters, giving indication of the duration and intensity, apply equally well to the total storm rainfall as to the 24 hour amount. It would be desirable to take into account possible changes in these factors as the situation develops, in other words, to attempt to forecast the changes in the forecast parameters, which in turn would affect the amount occurring during the latter part of a storm lasting more than 24 hours. Introduction of additional developmental parameters would, from the synoptic standpoint, involve such aspects as advection of temperature changes and development due to dynamic instability, aspects which cannot be readily reduced to simple predictors. For the present it appears desirable, therefore to test the applicability of the predictors for the 24 hour amounts to the storm totals as well.

A criterion for defining the duration of a storm in terms independent of the rain is desired. That such a criterion is needed is illustrated by the period of March 2 to 5, 1949, during which a single storm from the meteorological standpoint was present, with a low center remaining stationary off the coast near San Francisco throughout the period. Variations in flow produced cessation of the precipitation at Maricopa and Taft on the 2nd, with resumption on the 4th, making it appear from the precipitation amounts to be two storms. Cholame Hatch Ranch, on the other hand had rain every day of the period, and San Francisco had at least a trace of rain every day from March 1 to March 11, but that of the latter part (March 8-11) was due to a second storm

from the meteorological standpoint.

For the more intense storms, which include most of those causing rain in the C-T area, the period during which the pressure reduced to sea level at Santa Maria is less than 1010 mb would be a good criterion. There would be a number of cases omitted by this criterion, however. In general rain in this region begins after the pressure has been falling for some time, and ends shortly after the pressure begins to rise. Since not all cases of falling barometer are accompanied by rain, use of this variation would have to be signalled by the beginning of rain: if rain begins after the pressure has been falling (the usual case), the duration of the storm rain shall be from the time of that beginning until the time of the ending accompanying or following the beginning of a rise in pressure. This hybrid criterion would cover all but a small number of rains, and the exceptions would invariably be light and of short duration.

APPENDIX F
AND ADDENDA

REPORT ON
CLASSIFICATION OF STORMS
FOR STATISTICAL EVALUATION
WITH SPECIAL REFERENCE TO
CARRIZO PLAIN AND SANTA MARIA COASTAL AREAS

Report to the Division of Water Resources
Department of Public Works
State of California

By Edward M. Vernon
Chief Regional Forecaster
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February, 1953,
May, 1953, and
October, 1953

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REPORT ON

CLASSIFICATION OF STORMS FOR STATISTICAL EVALUATION, WITH SPECIAL REFERENCE TO CARRIZO PLAIN AND SANTA MARIA COASTAL AREAS

The purpose of this study is to develop, through meteorological reasoning and synoptic experience, criteria which may be used to so classify various rain producing situations in California that the regression of rainfall in one area (target) on that in another area (control) is different in a storm of one classification from that in another.

In dealing with this problem we shall make full use of the well known fact that seasonal isohyetal patterns in California are strongly influenced by the effect that the State's many mountain ranges have upon the natural rain producing processes. This effect is so great that in general the seasonal isohyetals run parallel to the topographic contour lines. Furthermore, a glance at the normal isohyetal map for the State will serve to illustrate how two localities such as Santa Cruz and San Jose, one of them located on the windward and the other on the lee side of a mountain range, can have widely differing seasonal precipitation even though both are at about the same elevation.

The large differences in annual precipitation represent the cumulative effect of all storms occurring during an average year. But since the effect of topography on the amount received is so great, and since that effect depends to a great extent on the aspect of the mountains to the rain bearing winds, it is to be expected that the rainfall intensity patterns for storms having abnormal flow patterns might differ significantly from the normal seasonal distribution.

While a large part of the total precipitation in California is orographic in nature, it occurs for the most part in conjunction with the passage of frontal disturbances from the Pacific. We should, therefore, consider the influence of mountain ranges on the fronts and the precipitation associated with them.

Figure 1, patterned after Petterssen's example, (1) illustrates successive stages of a WARM FRONT crossing a mountain range. It is an east-west section of the mountain range with the warm front surface (inclined broken line) moving across it from west to east. In Panel A the frontal surface is west of the range and too far away to be influenced by it. In Panel B the frontal surface above the lee slope decreases and become nearly horizontal. This has the effect of reducing the upward motion of the air and preventing more than light precipitation over that slope. Farther east and at higher elevations the frontal surface retains its original slope. West of the mountains the lower portion of the warm front is retarded, causing a stationary frontal surface to persist over the windward slope, thus prolonging rain in that area. In Panel C the stationary warm front persists over the windward slope. The portion of the front above the level of the mountain range has moved east while the downward motion of the air along the lee slope has caused the frontal cloud there to dissipate. In Panel D the stationary warm front west of the range has finally eroded and rain there has ended. At higher altitudes the portion of the warm front not cut off by the mountain range has moved off to the east as an upper front.

Figure 2 (also patterned after Petterssen's example (1)) illustrates the successive stages of a cold front passing from west to east across a mountain range. Here again it is readily seen that conditions call for more precipitation on the windward than on the lee side.

In summing up the effect of mountain ranges on frontal systems, Petterssen (1) has this to say:

> "---The influence of a mountain range on a front is characterized by: (1) widening of the frontal area of precipitation as the front approaches the range. (2) prolonged duration and increased intensity of frontal precipitation on the windward side. (3) narrowing of the area of precipitation or dissolution of the frontal cloud on the lee side of the range -----"

Not all precipitation is frontal in origin. Rain or snow often occur due to lifting caused by convergence of air streams in advance of an approaching LOW pressure system. Also, showers frequently occur in unstable air masses preceding or following a front. In such cases the precipitation process will be strengthened by the forced ascent of air on the windward slope and hindered by the descending air on the lee slope. Hence, whether precipitation be of frontal origin or not, there should be a tendency for it to be heavier on the windward than on the lee slopes. A possible exception might occur when the air mass below the mountain crests on the lee side is moist, thermodynamically unstable, and warmer than the air flowing across the mountain. In this case the colder air could overrun the warm moist air on the lee side and set off heavy showers and thunderstorms. This would not often occur in California but may happen occasionally in the spring season and so should be kept in mind as a possible explanation of unusual rainfall patterns.

Going forward with this line of reasoning we should expect that the difference in amount of precipitation received in two areas, one on the windward and the other on the lee side of a mountain range, would be greatest when (1) the component of air flow normal to the mountain range is large while the storm is in progress and (2) the frontal surface approaches the range broadside, i.e. is delineated on the surface map by a line running parallel to the range. This is illustrated schematically in Figures 3A-D. In Panel 3A the air flow is from the southwest and normal to the range. At the same time the approaching front lies parallel to the range so that it approaches broadside. Here we would expect a maximum difference in precipitation in areas 1 and 2, with area 1 receiving the greater amount. Conversely, under conditions pictured in Panel 3B, with both wind and frontal surface approaching from the northeast we should expect at least as much and probably more precipitation in area 2 than in area 1.

Conditions depicted in Panels 3C and 3D show the wind flowing parallel to the range while the frontal surface is oriented at right angles to and is moving along it. These conditions would tend to equalize the precipitation in areas 1 and 2, though the area lying on the side of the range having the most direct access to moisture bearing winds would logically be expected to receive the greater amount. Proximity to the LOW pressure center would also be a factor in some cases.

The applicability of these concepts was demonstrated by Johansen (2) in his study of storm rainfall distribution in northern Norway. The mountain ranges in that area are oriented roughly northeast-southwest. Johansen showed by means of selected storms that with fronts approaching from the southeast, south, or south-southwest the heavier amounts of precipitation fell on the east side of the mountains. With fronts from the southwest, west or northwest the heavier amounts occurred on the western side. In each instance the side receiving the heavier amounts was the windward. The same relation between distribution pattern and wind direction prevailed when showery precipitation occurred without fronts.

Judging from the pronounced differences which Johansen found in precipitation patterns, classifying solely on storm wind direction (or direction from which front approached), one might expect to obtain satisfactory results by applying that method alone to storm classification in California. To test this hypothesis, prevailing wind direction at Santa Maria was studied in connection with all storms in that part of the State from 1945 to 1951. Wind was taken at hour of maximum rainfall or the last preceding measurement before that hour. Winds for the 6,000 and 12,000 ft. levels were considered. Rainfall amounts for four stations on the coastal side of the coast mountains was compared with that at four stations on the inland side. This was done for various wind

directions. While the expected relationship between distribution pattern and wind direction was present to some extent, it was not so pronounced as that found by Johansen in northern Norway.

Perhaps this should have been expected, since Johansen's study dealt with selected examples and did not include the many storms having borderline characteristics. At any rate, the preliminary correlation of storm isohyetal pattern to wind direction in the Santa Maria area indicated that additional factors must also be of considerable importance in determining the effect of mountains on those patterns.

Returning now to Figures 1 and 2, it is readily seen that the extent to which precipitation on the lee side of the mountains is reduced or eliminated should depend to a considerable extent on the height of the mountain range and the vertical extent of the frontal surface. If the frontal surface is of only about the same vertical extent as the mountain range, most of it will then be cut off by the mountains and very little will remain to produce precipitation to the leeward. On the other hand, if the vertical extent of the frontal surface is great compared to the altitude of the mountain range, then a relatively small percent of it will be cut off while that part lying well above the mountain crests will be free to move across undisturbed, producing precipitation on the lee as well as the windward side. This should apply to both warm fronts and cold fronts. Moreover, it applies as well to instability showers. Other things being equal, the greater the height to which instability shower clouds can build the greater will be the tendency to equalize precipitation amounts on the windward and lee sides of the mountain range.

We should, therefore, expect to find the difference in precipitation to windward and lee of a mountain range at a maximum when (1) wind and frontal movements are normal to the range, (2) frontal disturbances are of small vertical

extent, and (3) vertical stability is great. Similarly, we should expect the difference in precipitation on the two sides to be at a minimum when (1) wind and frontal movements are parallel to the range, (2) frontal disturbances are of great vertical extent, and (3) vertical stability is slight. What we need then in a typing system are measurements which will be related directly or indirectly to these three factors. For the past several years we have been able to obtain, through rawindsonde observations, the direction and force of wind at upper levels twice a day. However, we have no direct measurements of the vertical extent of frontal systems, and even the measurements of vertical stability are scarecely adequate for our purpose. Vertical stability depends to such an extent on moisture charge of the air and this can change very rapidly with the approach of a frontal trough. A radiosonde observation taken a short time before or after a frontal passage on the Pacific coast may give a very poor indication of the vertical distribution of moisture along the front itself. Another factor complicating this aspect of the problem is the fact that we have no radiosonde observations in the area immediately offshore (within 800 miles) and consequently we do not obtain a representative sounding of either frontal depth or vertical stability as the storm front or unstable air mass approaches the coast.

As a result of these deficiencies we must seek indirect criteria which will be sufficiently related to the frontal depth and vertical stability factors to permit us to use them in the proposed typing procedure. At this point it will be well to ask ourselves what is the simplest and most easily applied system of map typing. The answer to this question is, very likely, that system which types according to the general circulation index. In this system, originated by Rossby (3) and used extensively by Namias (4) and Willett (5), maps are classified as "High Index" or "Low Index" depending on the strength of

the west-east air movement in middle latitudes. In High Index situations there is very rapid west-east movement. Sinusoidal waves are set up in the westerly or zonal current but they remain relatively flat, i.e. of small amplitude, so that there is no great meridional displacement of the air masses and, consequently, no great confluence of cold air masses from the north with warm air masses from the south. Conversely, under Low Index situations the west-east movement is, by comparison, slow; the sinusoidal waves or perturbations set up in this west-east current are of large amplitude so that there is pronounced meridional displacement of the air masses. Warm air masses are carried far to the north and cold air masses far to the south. There is often much confluence between these two masses, resulting in strong horizontal temperature gradients and strong fronts. This type of flow often leads to cut-off cold LOWS aloft, giving rise to deep masses of cold, thermodynamically unstable air in which convective cells can build to great heights.

We should expect that storms occurring under High Index circulation conditions would have relatively shallow fronts and stable air masses, and that they would approach the coast from a westerly direction. Both of these effects would tend to accentuate the orographic component of precipitation associated with mountain ranges running northwest-southeast. In contrast, storms occurring under Low Index circulation conditions would have relatively strong fronts and unstable air masses, and would approach central California from a northerly or northwesterly direction, or in some cases from a southerly direction if on the east side of a stationary Low Index trough. Both of these effects would, according to our reasoning, tend to equalize precipitation on the east and west sides of the mountains and thereby reduce the orographic component of precipitation associated with mountain ranges running northwest-southeast.

One might conclude from this that we could accomplish our purpose by typing storms as High or Low Index, using for this purpose the zonal indices recorded by the Extended Forecast Section of the Weather Bureau for the past 12 or 15 years. However, we encounter here a difficulty arising from the fact that those indices are evaluated for the entire northern hemisphere. As a result of this it is quite possible for a fairly extensive area, as for example our west coast, to be in the first or last phase of one type of zonal flow while the hemisphere as a whole shows the opposite type. It is therefore desirable for our purpose to take a sampling of the flow over a smaller area in order that we obtain an index which is more representative of the conditions prevailing along our coast at the time of the storms being evaluated.

Several typing systems applicable to our west coast have been developed which make use, directly or indirectly, of the concept of High and Low Zonal Index. For example, Reed (6) described a system in which his so called "northerly type" was definitely a Low Index situation while his "westerly type" was of the High Index category. But Reed's system was slanted for forecasting a day or two in advance. This weakens it for use in our problem which seeks to type the current synoptic maps for correlation with concurrent precipitation patterns. The same difficulty is encountered in attempting to use certain other typing systems such as those developed at California Institute of Technology (7) and by Elliot (8), which were designed for forecasting several days in advance. For our purposes the objective typing procedures used by Thompson (9) and Vernon (10) have the same drawbacks in greater or less degree.

To satisfy our needs, the typing system must be based on parameters that are so closely related in time and space to the actual rain storm under consideration that they will give a reliable index as to whether that particular storm is behaving as a High or a Low Index type at the time it is causing precipitation in the area with which we are concerned. This means that we must

select the map time in such manner as to make the map and storm times concurrent so far as practicable. To accomplish this it is convenient to deal with the synoptic map coinciding with the hour of greatest precipitation or, if this is not possible, the map next preceding the hour of greatest precipitation.

Having decided thus which map to tie in with a given storm, we can proceed to examine representative storms of both High and Low Index types at map times most closely associated with rain in a selected area. For this purpose the area represented by rainfall recording stations at Santa Maria, San Luis Obispo, Huasna, Paso Robles, Cholame, Lost Hills, Middlewater, and Taft was selected. This in turn was divided into two sub-areas, one represented by the first four stations and called the control area; the other represented by the last four stations and called the target area. The control area lies for the most part west of the coastal mountains while the target area lies to the east of them. In the mean, the control area receives more than twice as much precipitation as the target area, the ratio of target to control being about 0.37.

Figure 4 shows a good example of a Low Index type. This does not necessarily mean that the entire hemisphere would have a low circulation index, but rather that the circulation along and off our west coast is typically Low Index. We have a LOW center over Nevada and a HIGH off the coast with its major axis oriented north-south. Isobars off the northern California coast run north-south and there is a strong west-east pressure gradient there. A secondary cold front at the Oregon border is in a position to move almost directly south. Pressure contours at the 10,000 ft. level (shown by dotted line) have the 700 millibar isobar running southward from Alaska to the latitude of southern California before curving eastward, thus indicating a very large amplitude in the westerly waves, with great displacement of cold air from high to low latitudes.

Note too that the surface pressure is considerably higher off the extreme northern California coast than at Santa Maria. According to concepts developed earlier we should expect that this Low Index storm, with its distinctly meridional type flow pattern, should tend to equalize the precipitation in the two areas mentioned in the last paragraph. In fact, there is some indication that the east or valley side of the coast range may prove to be the windward side as the storm front passes, and in such event the valley stations (target area) may actually receive more precipitation than the coast stations (control area). This is in fact what happened, with Cholame, Lost Hills, Middlewater, and Taft receiving a combined total of 0.38 inch compared to a combined total of 0.26 inch received by Santa Maria, Paso Robles, San Luis Obispo, and Huasna.

Figure 5 shows another example of the Low Index type having a pronounced meridional flow pattern. In this case the LOW center is over the northern California coast while the Pacific HIGH cell is a little farther west than in the last example. As before, the isobars off the coast are oriented north-south and there is a strong west-east pressure gradient. Also, it will be seen that the 10,000 ft. height contour on the 700 millibar pressure surface (dotted line) swings through a very wide range of latitude in such manner as to be associated with the southward transport of cold air off our coast. It will also be noted that in this case we have a cut-off cold LOW at the 700 millibar level, as shown by the 9,600 ft. height contour line. As in the preceding example we see that the pressure off the northern California coast, in the vicinity of the 130th. meridian, is considerably higher than at Santa Maria. However, due to the intervening cold LOW aloft we have southerly flow indicated at Santa Maria. Thus we have a situation suitable for strong advection of cold air from higher latitudes and yet we have southerly flow aloft at Santa Maria. This then is logically a special case of the Low Index

type in which upper flow at Santa Maria is southerly instead of northerly. This storm produced 0.30 inch of rain at Cholame, Lost Hills, Middlewater, and Taft and 0.64 inch at Santa Maria, Paso Robles, San Luis Obispo, and Huasna. This is a ratio of 0.47 (target to control), which is somewhat higher than the normal ratio but still not so favorable to the target area as the Low Index type having northerly flow along the coast.

Figure 6 illustrates a storm of the High Index type. In this case the zonal or west-east flow is much greater at the latitude under consideration than the meridional flow. For example, it will be noted that in the area off the California coast (about the 130th. meridian) the isobars run west-east instead of north-south as they did in the two preceding examples. Also, there is a strong south-north pressure gradient in that critical area, in contrast with the strong west-east gradient noted there in the meridional flow patterns. Superimposed on the surface map is the 10,000 ft. contour of the 700 millibar chart. It will be noted that this contour runs generally from west-southwest to east-northeast, having a series of waves that are relatively flat as compared to the large amplitude waves characteristic of the meridional flow patterns. At no point between our coast and the 160th. meridian does this contour reach north to latitude 40°, and it therefore does not represent an upper flow situation favorable for transporting cold air masses south to the central California coast. Here we have a map which combines three features all of which are strongly favorable to a large orographic component of precipitation on the coastal side of our mountains. They are: (a) strong west-east or southwest-northeast flow in the lower levels, (b) frontal passages from west to east, and (c) an upper flow pattern incapable of sustaining cold air advection along our coast. True to expectations, the coastal stations received much more precipitation than the interior group, 10.80 inches against only 0.60 inch. Before passing from this storm it should be noted that the

pressure off the northern California coast, say at 40°N 130°W, is much lower than at Santa Maria. In the meridional flow patterns this relationship was reversed.

Study of these and other outstanding examples of High and Low Index storms that caused precipitation at one or more of the eight stations in the area under consideration, led to the decision to classify all storms into one of two broad, general types depending on whether the pressure at Santa Maria was higher or lower than that at 40°N 130°W, Eureka, and San Francisco. If the pressure at one of these three points was equal to or higher than at Santa Maria, the storm would be placed in general Class I; if not it would be placed in general Class II. This is noted symbolically as follows:

$$\text{Class I}: \quad P_{40N130W} \text{ or } P_{EKA} \text{ or } P_{SFO} \geq P_{STH}$$

$$\text{Class II}: \quad P_{STH} > P_{40N130W}, P_{EKA}, P_{SFO}$$

Where P denotes pressure measured at the surface and the subscripts designate points of measurement as follows: EKA for Eureka; SFO for San Francisco; and STH for Santa Maria.

It will be readily evident from earlier comments that Class I corresponds in general to the Low Index or high meridional flow type while Class II corresponds to the High Index type having strong zonal flow. Class I will favor the target area by tending to equalize precipitation amounts regardless of the topographic aspect. Class II will tend to favor the control area represented by Santa Maria, Paso Robles, San Luis Obispo, and Huasna.

It was noted in studying Figure 4 that the condition most strongly favoring the target area was that in which a front can move down from the north. These situations are comparatively rare, but study of additional storms indicated that a significant number of cases could be placedin this restricted category without too much loss of class characteristics by including all Class I situations in which: (a) the 6,000 or 12,000 ft. wind direction at Santa Maria

was from northwest to east, inclusive or, (b) either the 6,000 or 12,000 ft. wind at Santa Maria was from the West-northwest and the pressure at 40°N 130°W was 1020 millibar or higher or, (c) pressure at 40°N130°W was equal to or greater than 1024 millibar regardless of wind direction. If any one of these three conditions prevailed, the map was placed in Class I_a, which is the one most strongly favoring the target area.

Figure 5 depicted a Class I storm in which Santa Maria winds were southerly instead of northerly. Study of other such cases lead to the conclusion Class I storms not qualifying as Class I_a would still favor the target area to a considerable degree if the Santa Maria winds at 6,000 or 12,000 were from either south or south-southwest. This then became the basis for another classification, Class I_b which, as indicated, favors the target area though not so strongly as does Class I_a.

All remaining cases of Class I were relegated to the Class I_c. This category includes, for the most part, those Class I cases in which the winds aloft are from west, west-southwest, or southwest. In the mean it seems to favor neither the targetnor the control area. The ratio of target area to control area rain for this type averages very close to the normal seasonal ratio of rain for the two areas.

Dealing with storms in general Class II posed new problems. Storms of this category occurring when pressure at Santa Maria was relatively high seemed to favor the control area more than those occurring when Santa Maria pressure was low. This could be explained by assuming that storms occurring during high pressure would be in a field of upper air convergence and subsidence and would therefore be relatively stable when passing the area under consideration. They should therefore not be of great vertical extent, thus permitting a large percent of the frontal surface to be cut off in passing across

the mountains. As we reasoned earlier, this would tend to deprive the target area (which in this case would be to the lee of the mountains) of precipitation. Conversely, if a Class II storm passes when pressure at Santa Maria is relatively low, there may on occasion be considerable convergence preceding or accompanying the front, thus permitting it to build to sufficient height to yield significant rain on both sides of the coast mountains. However, there does not seem to be a clear cut dividing line between the two extremes of high and low pressure. The storms were therefore divided so as to give about the same number of cases in the high pressure classification as in the low pressure class. This was accomplished by tentatively placing in Class II_a all Class II storms having pressure at Santa Maria equal to or greater than 1016 millibar. Those with Santa Maria pressure less than 1016 millibar were classed as Class II_b.

It will be recalled that the basis for placing storms in general Classes I and II was the relationship between pressures at Santa Maria and three selected points to the northwest. This step produced good results for Class I, but in dealing with Class II it was found that it placed in that general class a fairly large number of storms partaking of Class I characteristics. It was therefore found advantageous to set aside those Class II storms in which the pressure at 40°N 130°W was within 4 millibar of being as high as that at Santa Maria. This required dropping from Classes II_a and II_b a number of storms originally included, and placing them in this new category. With this step accomplished, Class II was then effectively divided into three categories as follows: Class II_a in which pressure at Santa Maria was 1016 or higher and over 4 millibar greater than pressure at 40°N 130°W; Class II_b in which pressure at Santa Maria was less than 1016 millibar but still over 4 millibar higher than at 40°N 130°W; and Class II_c in which pressure at Santa Maria was higher than at 40°N 130°W but not over 4 millibar higher. The first of these

strongly favors the control area; the second favors the control area but to a less degree than the first; the third if fairly neutral as was the case with Class I_c.

A summarization of the typing criteria is presented in Table 1. Also included is a brief statement to indicate which types should be expected to favor the target and which the control area. Using these criteria, all storms occurring in the subject area were typed for the period January 1945 to September 1951, inclusive. These data have been turned over to the U. C. Statistical Laboratory for their use and evaluation.

TABLE 1

OUTLINE OF CLASSIFICATION CRITERIA AND CHARACTERISTICS

Class I: $P_{40°n\ 130°w}$ or P_{EKA} or $P_{SFO} \geq P_{STH}$		Favors target area
Class I_a :	(1) STH wind direction at 6,000 or 12,000 ft. from NW, NNW, N, NNE, NE, or E or	
	(2) STH wind direction at 6,000 or 12,000 ft. from WNW and $P_{40°n\ 130°w} \geq 1020$ mb. or	Strongly favors target area
	(3) $P_{40°n\ 130°w} > 1024$ mb. regardless of STH wind.	
Class I_b :	Class I cases not qualifying as I_a and having STH 6,000 or 12,000 ft. wind direction as S or SSW	Favors target area but not so strongly as I_a
Class I_c :	Includes Class I cases not qualifying as I_a or I_b	Neutral
Class II: $P_{STH} > P_{40n\ 130w}$, P_{EKA}, P_{SFO}		Favors control area
Class II_a :	$P_{STH} \geq 1016$ mb and $(P_{40°n\ 130°w}) + 4 < P_{STH}$...	Strongly favors control area
Class II_b :	$P_{STH} < 1016$ mb and $(P_{40°n\ 130°w}) + 4 < P_{STH}$...	Favors control area but not so strongly as II_a
Class II_c :	$P_{STH} \leq (P_{40°n\ 130°w}) + 4$	Neutral

Although it was not the object of this project to make a thorough statistical analysis of the data, the writer computed regressions for target on control precipitation for each of the types separately and for all combined. Figure 7 shows the regressions for Classes I_a and II_a and for all classes combined. It is readily apparent that if a cloud seeding operator had seeded during this period, and if he had been clever or fortunate enough to have seeded only Class I_a storms, he could point to the regression for seeded storms (which would have been coincident with that for I_a) and by comparing it with the regression for all storms lay a rather convincing, but as we can see invalid, claim to having produced a large increase in rainfall.

On the other hand, if he had been so unfortunate or unwise as to have seeded only Class II_a storms, and moderate increase in precipitation which he might have brought about could easily have been obscured by the expected difference between the regression for that type and the one for all types combined.

Thus we can see that in an area where topography exerts a great influence on rainfall, and where that influence apparently varies with storm type, one may obtain misleading results if he attempts to evaluate cloud seeding efforts by the control area method (in any of its various forms) without taking into account the extent to which the relationship between control and target rainfall may vary with storm type.

Figure 8 shows the regressions of target on control rainfall for all six classes, which were also computed by the writer. It is apparent that, with the amount of data available, the difference between some of the classes may not prove significant when subjected to rigorous statistical tests which are to be conducted by the U. C. Statistical Laboratory. In this event it will be a simple matter to combine the classes not showing significant differences.

It is the belief of the writer that the typing criteria herein presented are probably not the best that could be developed for the area under consideration. It must be realized that these criteria were selected largely as a result of inductive reasoning and synoptic experience. It is logical to assume that by using them as a starting point one could, by successive steps of approximation, select even better and more effective criteria. However, it is doubtful that such a process would yield an improvement of over 10 per cent in the segregation by types, and it would be a process involving a great deal of clerical effort.

Another thought which may be of considerable importance is that a shrewd synoptic forecaster might be able to select only the outstanding storms of each type for seeding purposes. For example he might be able to select for seeding only those type of Class I_a storms that would fall above the regression line; and similarly for other classes. For this reason, decision as to which storms to seed, or which seeded storms to evaluate, should not be left to the will of a shrewd weather forecaster.

In conclusion it seems appropriate to suggest a procedure for developing a map typing system for any given area for the purpose of differentiating between target and control rainfall to be expected under different map types. The following two procedures are devised to bring out differences in orographic rainfall. One is designated the "Long Procedure" and the other the "Short Procedure". Neither is actually a short procedure so the two designations have only relative significance.

LONG PROCEDURE FOR DEVISING A TYPING SYSTEM FOR CLOUD SEEDING EVALUATION

1. Decide which synoptic and upper level maps will be associated with each storm.

2. Have a meteorologist of long experience in forecasting from synoptic weather types examine each storm, (map for each storm) and classify it into one of at least two but not more than four or five basic types predicated on the flow pattern principle.

3. Have a clerk refer to all storm maps and extract surface pressure and 700 millibar heights for a representative grid of points extending at least 1,000 miles in all directions from the area under study.

4. From these data compile mean maps for each type.

5. Subject these mean maps to statistical analysis to detect points of most consistent difference between types....as typed under step 2.

6. Use the points determined in step 5 to make an objective classification of all storm maps.

SHORT PROCEDURE FOR DEVISING A TYPING SYSTEM FOR CLOUD SEEDING EVALUATION

1. From past records select 30 or 40 storms which can be divided into two groups such as to show diametrically opposed relationships between target and control rainfall. If practicable draw these from a period or record not to be used in later steps.

2. Have a meteorologist of long experience in synoptic forecasting from weather types examine the maps for all these storms and classify them into not less than two nor more than four groups. (types to be based on flow pattern principles).

3. Have the same meteorologist select, from subjective evaluation of these maps, points where surface pressures and/or 700 millibar heights are characteristically consistent within a given type (or where pressure or height differences between two points are characteristically consistent within type). Use these pressure points or differences in an objective classification scheme.

4. Have a clerk go through <u>all</u> storms for the period that is to be studied and extract data for the points so selected. Use these data to classify all storms by the objective process evolved in step 3.

References

1. Petterssen, Sverre, Weather Analysis and Forecasting, New York, McGraw Hill, pp. 298-302, 1940.

2. Johansen, Sverre, On the Distribution of Precipitation in Northern Norway in Various Weather Situations, METEOROLOGISKE ANNALER, BD2, NR.11, Oslo, 1947.

3. Rossby, C. G., Relations between Variations in the Intensity of the Zonal Circulation and the Displacements of the Semi-permanent Centers of Action, Journal of Maritime Research, Vol. II, Number 1, June, 1939.

4. Namias, Jerome, Methods of Extended Forecasting, U. S. Weather Bureau, Washington, D. C., September, 1943.

5. Willett, H. C., Various reports on extended forecasting published by Massachusetts Institute of Technology and/or the U. S. Weather Bureau.

6. Reed, T. R., Weather Types of the Northeast Pacific Ocean as Related to the Weather on the North Pacific Coast, Monthly Weather Review, Vol. 60, No. 12, December, 1932.

7. Synoptic Weather Types of North America, Meteorology Department, California Institute of Technology, December, 1943.

8. Elliot, Robert D., Extended Weather Forecasting by Weather Type Methods, U. S. Navy Department. (Printed by U. S. Weather Bureau, February, 1944.)

9. Thompson, J. C., Progress Report on Objective Rainfall Forecasting Research Program for the Los Angeles Area, U. S. Weather Bureau Research Paper No. 25, Washington, D. C., July, 1946.

10. Vernon, Edward M., An Objective Method of Forecasting Precipitation 24-48 Hours in Advance at San Francisco, California, Monthly Weather Review, Vol. 75, No. 11, November, 1947.

FIRST ADDENDUM TO APPENDIX F
MAY, 1953

After completion of the preceding report, Mr. Vernon was asked to modify the procedures developed therein to develop a storm classification for the Southern Sierra area, 100 to 200 miles to the east of the area first considered. As explained in the report on the Southern Sierra evaluation (Appendix D), at first two comparison areas were selected. The Yosemite area is similar in topography and orientation to the Southern Sierra area, but about 100 miles farther north. The Valley area is on the floor of the San Joaquin Valley from Fresno to Newman. Mr. Vernon's brief report on this extension follows.

STORM CLASSIFICATION FOR

SOUTHERN SIERRA PROJECT

Selection of Key Map

In order to obtain good correlation between the synoptic conditions and precipitation pattern, we must consider the synoptic conditions best representing the main part of the storm. To make this possible we first try to determine which frontal trough is associated with the major part of the precipitation in a given storm. We then consider the synoptic map on which that frontal trough has passed San Francisco. If the front is approaching from the west or west-southwest, we use the map on which the point of nearest approach of the front to Fresno is no more distant from Fresno than is San Francisco. In some cases no frontal trough is detectable: in these we still attempt to use the map closest to but next preceding the period of major precipitation.

Yosemite vs Southern Sierra

If at time of key map, the 6,000 or 12,000 ft. wind direction at Santa Maria is from a point between west-northwest and east, we can expect that the front will have a decided southerly component of movement, i.e. movement toward the south. If it maintains its activity it may be expected to yield precipitation with equal effectiveness in both Yosemite and Southern Sierra.

However, if conditions are favorable for frontolysis as the front progresses southward, we may expect the Southern Sierra to be slighted. It has been noted that if the Santa Maria (STH) wind at 6,000 or 12,000 is from north of west at the time the front passes

San Francisco, and if at that time the pressure at Point Arguello is about 1019 mb., frontolosys does often begin, thus causing the Southern Sierra area to receive relatively less precipitation than under other conditions.

Using these considerations we can define two map types as follows:

Type I. STH wind at 6,000 or 12,000 WNW-N-E
POD pressure > 1019 mb. } Favors Yosemite

Type II. STH wind at 6,000 or 12,000 WNW-N-E
POD pressure < 1019 mb. } Favors S. Sierra

(The condition POD pressure = 1019 mb. is not covered. This omission is deliberate, in order to omit borderline cases.)

If at time of key map the 6,000 or 12,000 ft. wind at Santa Maria is from a point between west and east-southeast, conditions are favorable for a large component of orographic precipitation in both the Yosemite and Southern Sierra areas. If at this time the pressure at 40° N 130° W is equal to or higher than that at Point Arguello, the front is likely to move through with undiminished strength, thus favoring the Southern Sierra more than do those storms which diminish as they move through and which are often associated with lower pressure at 40° N 130° W than at Point Arguello.

Using these considerations we can define two more map types:

Type III. STH wind at 6,000 or 12,000 W-S-ESE
Pressure at 40°N 130°W < POD } Favors Yosemite

Type IV. STH wind at 6,000 or 12,000 W-S-ESE
Pressure at 40°N 130°W ≧ POD } Favors S. Sierra

San Joaquin Valley (Fresno-Mendota area) vs Southern Sierra.

Certain northerly storms tend to sweep southward along the Sierra Nevada, yielding fair amounts of precipitation over the mountains but relatively small amounts and sometimes none over the San Joaquin Valley floor. Conditions most favorable for this course of events are strong meridional flow with storm center far enough east to slight the Valley.

This is most likely to occur when pressure at 40°N 130°W is higher at key map time than that at Fresno, and when at the same time pressure at 35°N 130°W is more than normally high as compared to Eureka, and wind at 6,000 or 12,000 feet at Santa Maria northwest to east. Thus:

Type 1. Pressure at 40°N 130°W > FNO
Pressure at 35°N 130°W > EKA + 4
STH wind at 6,000 or 12,000 NWE
} Favors S. Sierra, at least when precipitation amounts are small.

In contrast, storms having pressure equal to or lower at 40°N 130°W than at Fresno, and at the same time having pressure at 35°N 130°W more than normally low as compared to Eureka, tend to bring frontal precipitation to the Valley. They cause precipitation in that area to be a little greater than normal as compared to the Southern Sierra. Thus two other types are:

Type 2. Pressure at 40°N 130°W ≦ FNO
Pressure at 35°N 130°W ≦ EKA + 4
} Favors Valley area.

Type 3. Storms not falling into either Type 1 or Type 2.

SECOND ADDENDUM TO APPENDIX F
OCTOBER, 1953

Subsequent to the issuance of Mr. Vernon's report, certain refinements of the typing method as applied to the Carrizo Plain study were made by staff members of the Statistical Laboratory of the University of California, following suggestions and advice offered by Mr. Vernon. In addition, the study of weather modification operations in Santa Barbara County was undertaken, using further refinements of the method developed by Mr. Vernon. Again, these refinements were made by members of the Statistical Laboratory staff, following suggestions put forth by Mr. Vernon.

The second addendum introduced hereby, was prepared by the staff of the Statistical Laboratory. It describes the refinements which were made, both for the Carrizo Plain study and the Santa Barbara County study.

Carrizo Plain. As described in this report (see page 178), the meteorological basis for placing storms in general classes I and II presented some complications and eventually produced the division of class II into three instead of two categories, of which the new class IIc was a class intermediate between the classes I and II.

Furthermore, as briefly described in Appendix C (see pages 97 to 99), Mr. Vernon's a priori hypothesis regarding such complex natural phenomena could not be expected to be exactly true. An inspection of Fig. 8 shows that the regressions for the various subclasses are in the order anticipated, but the two classes I and II overlap, with IIc being between Ib and Ic rather than below Ic. For this reason, the subclass IIc was returned to class I, being apportioned among Ia, Ib and Ic according to the direction of the wind in the upper air, just as class I itself had been split up. As described on page 99, this second classification system is thus composed of five classes: Ia' = original Ia plus one part of IIc; Ib' = original Ib plus another part of IIc; Ic' = Ic plus the remaining part of IIc; and the original classes IIa and IIb. The details of the divisions between the classes are shown on Plate F-2.

However, as also described on page 99, with the limited amount of data available, the differences between the classes Ia' and Ib' do not appear to be significant so they were combined into one class labeled class A, for brevity. For a similar reason,

the two classes Ic' and IIb were combined to form a composite class B. Then, for convenience in description, the last remaining class IIa, an original extreme subclass, is called C. This classification into A, B and C is now called, perhaps with injustice to Mr. Vernon, the third classification system of E. M. Vernon. It should be emphasized that two of the classes in this third system are presumably composite classes from a meteorological viewpoint. The third class C may well be also.

Appendix C indicates the statistical tests applied that lead us to state that the three true regression lines, corresponding to classes A, B and C, respectively, are different. Also (see page 112), efforts were made to split Mr. Vernon's groups into finer classes, still on a meteorological, nonprecipitation basis. These efforts failed.

Appendix C also tries to emphasize the fact that we have no way of knowing which of Mr. Vernon's three classification systems is preferable until we have access to new data. Also, as we have tried to indicate on several occasions (see pages 109 and 112, for example), we can never be sure that Mr. Vernon's system of classification is complete--that it should not be further divided. This means that the modified method of regression described in Appendix C can never be used as documentary evidence either for or against the effectiveness of cloud seeding. This can be supplied only by a randomized experiment.

Santa Barbara County. A classification of storms according to type was established on a meteorological basis for each of the five subtargets studied in Santa Barbara County. Thus, we

may expect the typing systems to be somewhat different in each of the five subtargets, as well as different from that employed in the Carrizo Plain area and that in the Southern Sierra area.

The classification of storms in Santa Barbara County was made after the classification for the Carrizo Plain area had been completed. Two of the subtargets are adjacent to the Carrizo Plain, namely Targets 1 and 5, and bear somewhat the same meteolcgical relation to their control area as the Carrizo Plain does to its control area. For this reason, Mr. Vernon suggested that his second or third classification system would be applicable. The available evidence indicates a classification system for these two subtargets intermediate between the second and third system. As expected, the estimated regression lines are not the same for the two subtargets. The 50 percent confidence intervals are shown on Plate 8. The classification system is less successful for Target 5; this may be due to the changing topographical aspect as one moves along this long, thin subtarget (see Plate 7).

Mr. Vernon also suggested that the presence of south to southeast high winds might play an important role in the classification system for Target 3. The data indicates that they are an important factor. Inspection of the confidence intervals for Target 3, also shown on Plate 8, shows that class Id', which are class I' storms for which the direction of the upper air is south to southeast (see Plate F-2), have a very different regression line from the other classes found. No other direction was found to be of importance so that class Ie' was formed of all the other

class I' storms. It happens that the regression line for this new composite class Ie' is not significantly different from that of the class IIb, and so these two classes were combined. This leaves only the extreme class IIa, which is also called C, remaining. It turns out to be significantly different from the other two.

Targets 2 and 4 are somewhat intermediate in character, with the south wind rather more important in Target 2 than in 4. Here, also composite storm classes are employed. For convenience, we set forth the definitions of all of these:

Class A = class Ia' + class Ib'

Class B = class Ic' + class IIb

Class C = class IIa

Class D = class Ia' + class B = class Ia' + class Ic' + class IIb.

As mentioned, the meteorological definitions of the classes Ia', Ib', Ic', Id', Ie', IIa and IIb are shown on Plate F-2.

As was the case in the Carrizo Plain classification, efforts to find a finer classification were not successful.

We should say here that Control Area No. 1 used for all the Santa Barbara County evaluation, was purposely taken as close to the coast as possible, north of Santa Barbara County, with the expectation that the type of differentiation described in the main part of this Appendix F would be achieved. The fact that this was achieved, with the logical variations for the different geographical aspects presenting themselves in the different subtargets, may be interpreted as evidence for the validity of the meteorological basis of the typing system.

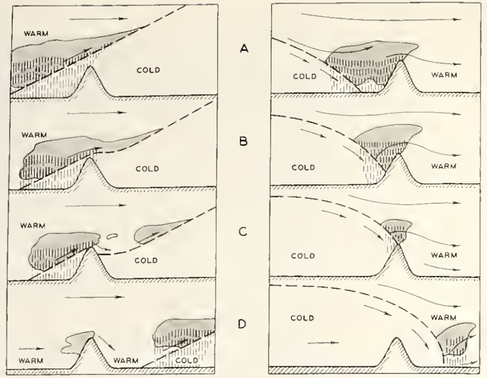


FIG. 1
SUCCESSIVE STAGES OF FRONTS CROSSING A MOUNTAIN RANGE

WARM FRONT

COLD FRONT

FIG. 2

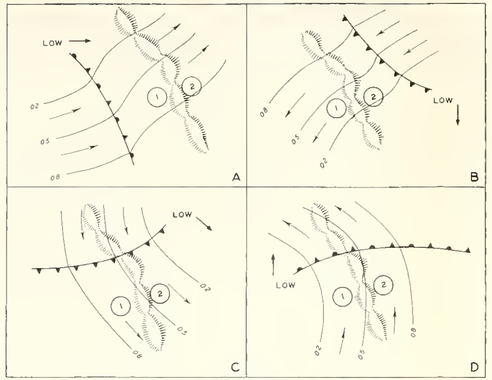


FIG. 3
TYPICAL ORIENTATIONS OF FRONTS WITH RESPECT
TO MOUNTAIN RANGE

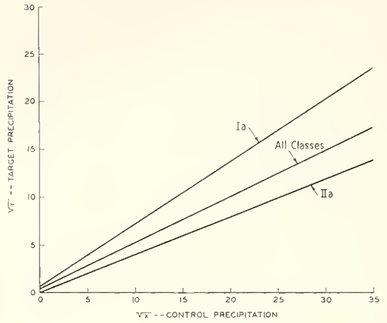


FIG. 7

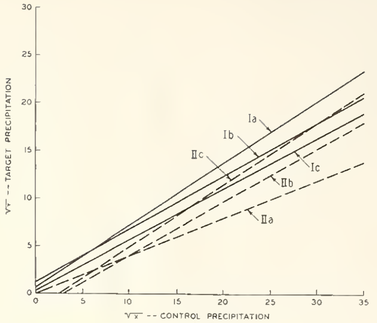


FIG. 8

RELATIONS BETWEEN TARGET AND CONTROL PRECIPITATIONS FOR STORM CLASSES

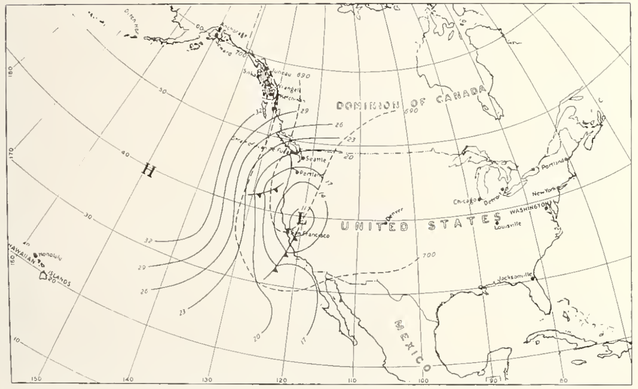


FIG. 4 SURFACE ISOBARS (10 A.M.) AND 10,000 FOOT ISOBARS (8 A.M.)
STORM OF FEBRUARY 27, 1945

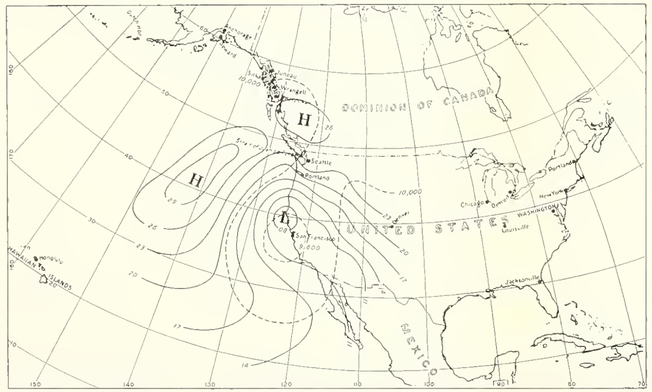


FIG. 5 SURFACE ISOBARS (4 P.M.) AND 700-MILLIBAR HEIGHT CONTOURS (8 P.M.)
STORM OF NOVEMBER 11, 1946

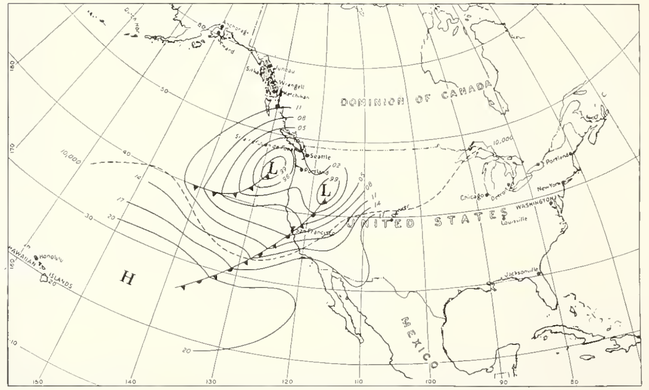


FIG. 6 SURFACE ISOBARS (10 A.M.) AND 700-MILLIBAR HEIGHT CONTOURS (8 A.M.)
STORM OF NOVEMBER 19, 1946

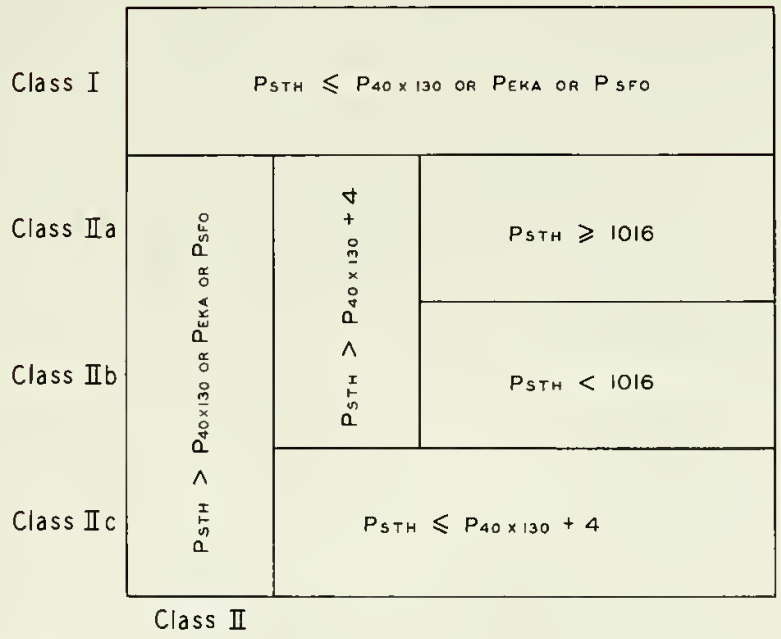
Figures 1 and 2 by permission from "Weather Analysis and Forecasting" Sverre Petterssen Copyright 1940 McGraw-Hill Book Company Inc.

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

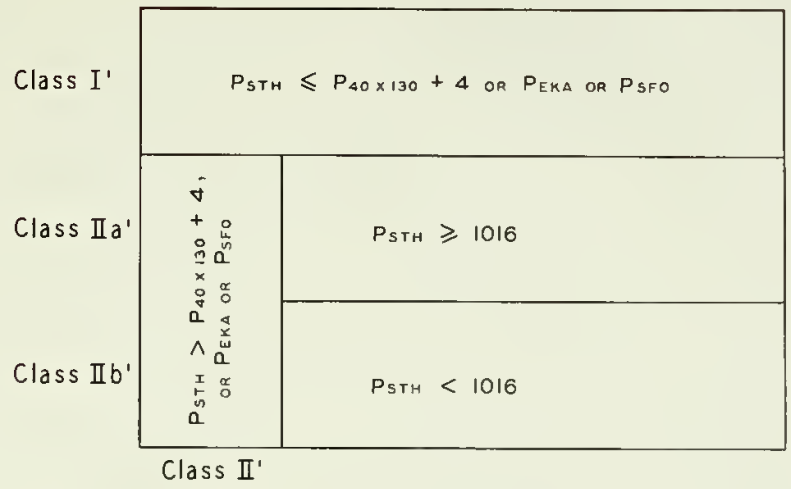
WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

FIGURES FOR APPENDIX F

PRESSURE CLASSES


Class I
PSTH ≤ P40 x 130 OR PEKA OR PSFO
Class IIa
Class IIb
Class IIc
PSTH > P40x130 OR PEKA OR PSFO
PSTH > P40 x 130 + 4
PSTH ≥ 1016
PSTH < 1016
PSTH ≤ P40 x 130 + 4
Class II

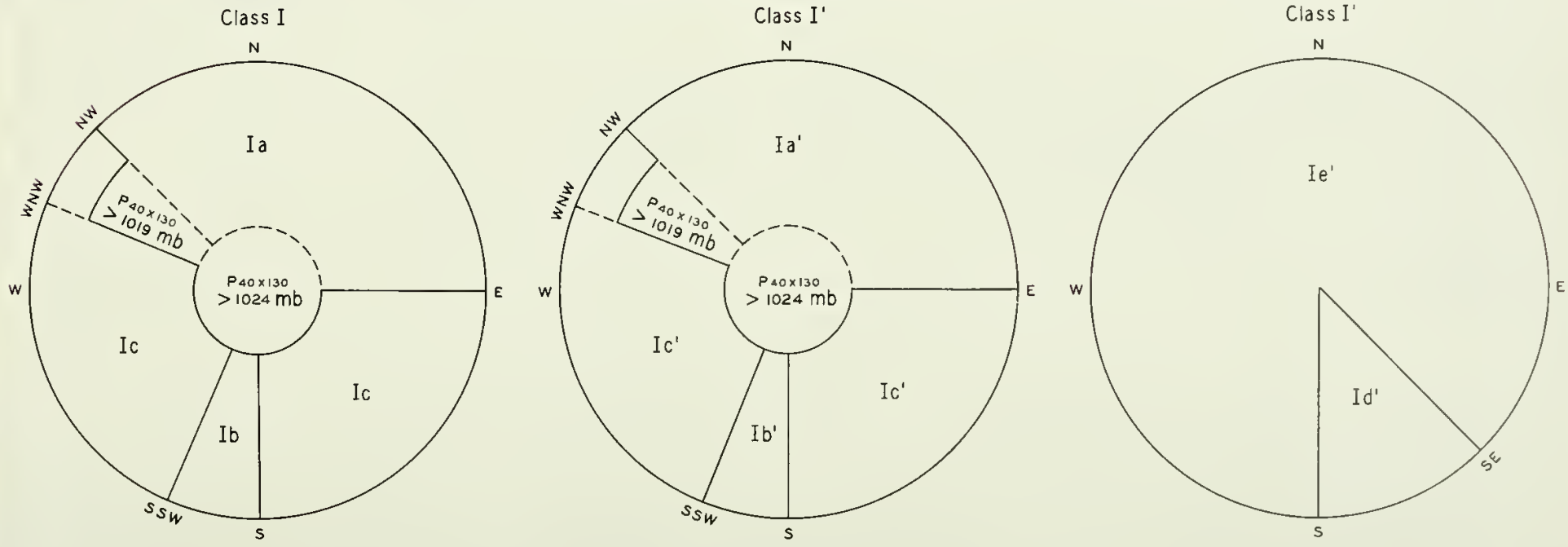
PRESSURE CLASSES



LEGEND

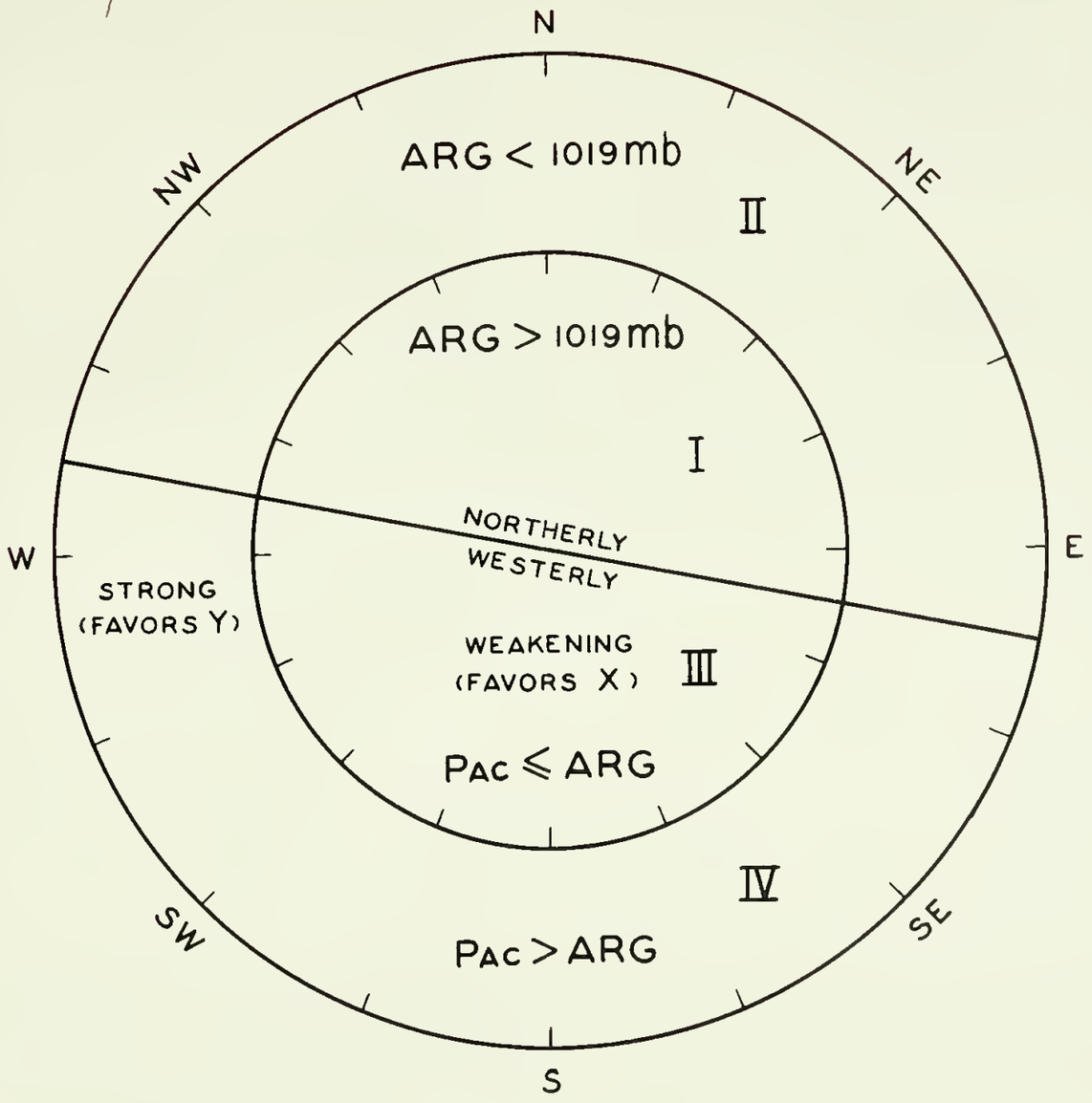
EKA	EUREKA
SFO	SAN FRANCISCO
STH	SANTA MARIA
40 X 130	LATITUDE 40 NORTH LONGITUDE 130 WEST

FURTHER CLASS I AND I' SUBDIVISION ACCORDING TO WIND DIRECTION AT STH



SCHEMATIC REPRESENTATION OF STORM CLASSES
FOR
CARRIZO PLAIN AND SANTA BARBARA COUNTY EVALUATION STUDIES

DIVISION OF WATER RESOURCES



LEGEND

ARG	POINT ARGUELLO
PAC	LATITUDE 40 NORTH LONGITUDE 130 WEST

SCHEMATIC REPRESENTATION OF STORM CLASSES FOR SOUTHERN SIERRA PROJECT EVALUATION STUDIES

APPENDIX G

A STUDY OF
THE MEASUREMENT OF SUBLIMATION NUCLEI
BY MEANS OF ICE CRYSTAL COUNT AND
THEIR ACTIVATION DUE TO TEMPERATURE

A Report to the Division of Water Resources
Department of Public Works
of the
State of California
on Work Performed at the
Institute of Engineering Research, University of California
Berkeley, California

Supervisors: J. T. Gier, Associate Professor of Electrical Engineering
R. V. Dunkle, Associate Professor of Mechanical Engineering
Project Coordinator: A. J. Test, Instructor in Electrical Engineering
Prepared by: N. W. Snyder, Assistant Professor of Mechanical Engineering
and
A. M. Dhanak, Associate in Mechanical Engineering

August, 1953

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A STUDY OF THE MEASUREMENT OF SUBLIMATION NUCLEI BY MEANS OF ICE CRYSTAL COUNT AND THEIR ACTIVATION DUE TO TEMPERATURE

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FIGURES

(All figures follow page 210)

1 through 8	Ice Crystal Count vs Temperature
9	Comparison With Published Data
10	Ice Crystal Count vs Temperature

INTRODUCTION

It is known that clouds which are below the freezing temperature of water will not produce snow if there is a dearth of effective nuclei (7) (9). These natural nuclei are of the order of size of 0.07 micron and consist of such materials as kaolin, other clays, carbon, sands and salts. Artificial introduction of nuclei has been conclusively demonstrated to cause snow formation and precipitation. It is also known that when a supercooled cloud reaches temperatures below -38.9°C, ice crystals will form spontaneously (4). As a consequence, it was also demonstrated that cold particles such as solid CO_2 (-78°C) could be dispersed through a cloud and cause snow formation and precipitation merely because of the local temperature depression below -38.9°C.

A certain amount of data, for the correlation of rain and snow fall with the number of natural nuclei present in the atmosphere, has been obtained. However, much more is needed, particularly in California, in order to evaluate the usefulness of artificial nucleation (seeding) for the production or prevention of rain or snow (11) (13). The construction and operation techniques of a nuclei counter was therefore undertaken as a project, by a group in Engineering at the University of California in Berkeley for and at the request of the State of California, Division of Water Resources.

In the originally approved proposal, the work outlined under this contract is divided into three parts as follows:

(1) During the first stage of work the Institute of Engineering Research will construct two standard cold box nuclei counters, determine the refrigeration characteristics, and adjust the operation of these instruments so that they may be installed in field stations.

(2) The second part of the program will consist in the adjusting of these instruments at the Weather Bureau observing station at Blue Canyon, California.

(3) The third part of the program, which, it is anticipated will be conducted under subsequent service agreements, will consist of the development and construction of a satisfactory nuclei counter which is portable and will operate through a complete range of temperatures of 0° to -40° Centigrade.

Verbal modifications of the above were made in a series of conferences between Mr. R. R. Reynolds of the Division of Water Resources of the State Department of Public Works, Professor R. V. Dunkle and Professor J. T. Gier; these changes were expedients that were followed as the over-all scope of the investigation shifted. The verbal modifications of the order, suggested changes as follows:

(a) Only one unit should be furnished.

(b) The money that was originally intended for the second unit should be used in exploiting one of the other phases of the proposed investigations. Thus, although item (1) was supposed to be the only part completed before proceeding with item (2), the staff was able to partially complete item (3). Therefore research carried out on the basic principles of nuclei counting was partially accomplished.

A deep-freeze unit was obtained which could be adjusted over a range of temperatures from $0^{\circ}C$ to $-40^{\circ}C$. A collimated light beam inside the box was porvided so that ice or snow crystals could be differentiated from liquid water droplets. The number of nuclei were counted by eye at various temperatures, which resulted in an interesting correlation between neclei count and temperature. An effect on this correlation, due to varying atmospheric conditions from day to day, was noted as well as that due to addition of extra nuclei. A spark discharge in the cold chamber caused spectacular results. The exploitation of this research was carried out in the order as follows: First, a cursory literature survey was conducted; secondly, a deep-freeze unit was obtained and experiments on nuclei formation, at one temperature, were performed; thirdly, nuclei formation, over a range of temperatures, was studied. The activities will be discussed in the order that the problem was attacked.

Literature Survey

There has been much research in the classification of the type and "activity"* of various nuclei which cause condensation of vapors to the liquid phase, condensation of vapors to the solid state and the freezing of water. The three major classifications presented serve to name three classes of nuclei, namely, condensation nuclei, sublimation nuclei and freezing nuclei respectively. There appears to be a controversy between Schaefer, on the one hand, who believes from experimental evidence (13) (12) that ice crystals are formed on certain foreign nuclei at temperature below 0°C and above 39°C by direct condensation of vapor to solid state, and others, such as Fournier d' Albe (4) and Weickmann (16), on the other hand, who claim that sublimation nuclei are extremely rare in all cases except below about -40°C. Houghton (7) points out that Schaefer's experiments were carried out under saturated conditions with respect to water which would corroborate the results of Fournier d' Albe and Weickmann. According to Ludlum (9) large increases in the numbers of crystals near -40°C are due to saturation with respect to liquid water. It is felt that this matter requires further study and for the present time, and for all intents and purposes, the ice crystals counted will be considered to have been caused by sublimation nuclei. One must be aware, however, that the ice crystal formed on certain nuclei in the laboratory cold chamber may not form in the same fashion as in the atmosphere because of the differences in air humidity.

The extensive research on ice nucleation, using a cold chamber, made by V. J. Schaefer, B. Vonnegut et al. of the General Electric Laboratory has been summarized in a Final Report on Project Cirrus (11). The report describes various

*A nuclei which is "activated" is one which will cause a freezing or condensation of water or water vapor respectively. A nuclei may become activated at a particular temperature.

types of cold chambers as well as artificial nucleation experiments utilizing such seeding agents as silver iodide and sodium chloride. By adiabatically expanding air in a Wilson cloud chamber, Vonnegut (14) has been able to produce low temperatures at saturated conditions needed for the study of formation of ice crystals. Cwilong (2) has made similar investigations with the Wilson cloud chamber method. Findeisen and Shulz (3) however, had already presented results with an expansion chamber on the number of ice crystal nuclei as a function of temperature, although they had not produced them using artificial nucleation.

Vonnegut and Schaefer (13) (15) advanced an explanation of ice crystal formation due to nuclei by noting the similarity of drystal structure of the ice particle and nuclei. This explanation fails to account for the formation of ice crystals by nuclei whose crystalline structure is not similar. However, Schaefer and Vonnegut did show that, although the ice crystals did appear for nuclei with less similar crystalline structure, the number produced was greater when the seeding agent had a more similar crystalline structure. One such substance was silver iodide. Schaefer states (13) that there are possible temperature dependent parameters such as size of basic crystal cell of the solid and nature of the surface layer and molecules for determining cryophilic and cryophobic surfaces. Cryophilic surfaces permit ice formation and cryophobic surfaces do not permit ice formation.

Hoseler (6) presented an alternate theory based upon a consideration of the surface energy of the water droplets in a supercooled cloud. He notes that all active materials provide ions or polarizable molecules which, upon entering the surface of the droplets, lower the surface free energy. This decrease of surface energy may permit the droplets to change to crystals. Heverly (5) ascribes the formation of most ice crystals to the spontaneous freezing of

the supercooled water droplets. This would indicate a count of condensation nuclei and not sublimation nuclei. Schaefer again points out that his photomicrographic studies of ice crystals (hexagon plates) does not indicate the formation of small frozen droplets. He states that seeding agents, such as silver iodide, raise the spontaneous freezing point but do not qualify the assertion by Heverly. Heverly experimentally showed that water droplets of 100/u in diameter freeze spontaneously at -25°C, as compared to the general value of -38.9 as determined by Schaefer. Heverly's correlation of snow crystal size as a function of freezing temperature appears significant.

Electron microscopic studies made by Schaefer (13), and Kumai (8) and Bentley and Humphreys (1) have revealed numerous internal structures of the snow crystal. Kumai was able to reveal the presence of foreign nuclei in the structure of snow crystals. He also presents a discussion of snow crystal growth.

Equipment

The equipment which finally yielded satisfactory results was developed around a 10 ft^3 ice cream cabinet provided with a manual thermostat to control the temperature from 0°C to -40°C within $\pm$ 1° C. A wooden lid was constructed to fit to fit the opening so that the interior could be isolated from the room. A room air sample was introduced a few inches from the floor of the freezer by means of a blower and a conduit fastened to the wood top. A slide valve was placed at the fan discharge to control the air flow.

A water vaporizer consisting of a 2" x 4" jar with an immersed heating coil (No. 30 B.S. gage constantan wire) was placed 4" from the floor of the freezer to permit supersaturation of the air. A variac in the heating coil circuit controlled the rate of evaporation.

A thirty watt sealed beam automobile spot lamp mounted on the lid, provided a collimated light beam which was reflected horizontally by a 4" x 4" metal mirror mounted at an angle of 45°. A No. 30 constantan wire heating coil was mounted on back of the mirror to defrost the front side during the time the box was warming. The variac controlled the voltage across this heater. The defrosting was necessary because the temperature of the high heat capacity metal mirror invariably lagged behind the freezer temperature and caused condensation or freezing of the excess water vapor. The power supply for the light source was supplied from a 6.3 volt transformer which was connected to a 110 v line. Masking of the mirror provided a means to form a collimated light beam of known thickness.

Visual observation of the water droplets and snow crystals in the light beam was made through a 2" diameter tube extending from a Plexiglas window in the lid to the light beam. One of several cardboard windows with 1 cm^2, 1/2 in^2 and 1 in^2 openings could be fastened to the light beam end of the viewing tube for snow crystal counts which were high, moderate and low respectively. A black velvet cloth provided the background for the observations.

The air temperature near the sample was measured by means of a Cu-Co thermocouple.

Procedure

With the blower running several minutes, a representative sample of air with its natural nuclei was introduced into the chamber. It is imperative that a fresh sample of air be introduced for each run, since the air which remains in the chamber after a run has had its natural nuclei washed out; the washing out having occurred when the water droplets and ice crystals, which were formed during the run collected on the walls of the cabinet. The sample introduced was first allowed to settle for 5 to 10 minutes, then a supersaturated cloud

was formed by means of the vaporizer, and the count was begun. After a lapse of approximately another 10 minutes, crystals were distinguishable from the water droplets since they shone more intensely because of their flat specular surfaces. (Schaefer indicates (12) (13) that these ice crystals are for the most part hexagonal plates.) Ten counts at five second intervals were taken and arithmetically averaged. During any one count the observer would survey the field of light through the viewing tube and make as accurate an estimate as possible of the ice crystals observed. The number of ice crystals per unit volume was computed by dividing the number observed by the viewed volume of the light beam. Temperatures were measured before and after the ten observations and averaged. It was found that the temperature varied by no more than $\pm$ 1°C during a run. The vaporizer and mirror heaters were turned off during measurements in order to maintain a more constant temperature and prevent circulating air currents within the chamber.

High counts of nuclei of the order of 10^6 per cubic meter necessitated the smaller 1 cm^2 viewing area whereas a low count of 10^3 per cubic meter or less required use of the whole cross section of the 2" diameter viewing tube. The light beam thickness for all runs was 4".

Because the general weather conditions appeared to affect the results, such meteorological measurements as wet bulb, dry bulb, wind direction, cloudiness and barometric pressure were noted approximately every two hours.

Three to four hours were necessary to obtain a set of data for temperatures from 0°C to -30°C. Reproducibility of data was checked for several points and data were taken with rising as well as decreasing freezer temperatures.

RESULTS

Included are results of ice crystal count as a function of temperature taken during the month of April, 1953, in the tunnel of Room 1, Mechanics Building at the University of California in Berkeley. The tunnel was ventilated with air through Room 1 which in turn was ventilated with outside air. Samples of air taken were felt to be representative of the ambient atmosphere. The data which have been presented in Figures 1 through 8 are for an ice crystal count with only natural nuclei present.

An attempt was made to artificially introduce nuclei by spraying a salt solution into the air near the freezer. Data has not been presented here but the results will be briefly discussed.

During some experimentation with the equipment, Mr. Dhanak discovered that the snow crystal count increased appreciably when an electric spark was formed at subzero temperatures within the chamber. Figure 10 shows a plot of snow crystal count versus temperature with several different materials used as electrodes.

Snow Crystal Count With Natural Nuclei Present

The accuracy of measurement was only tested in terms of the reproducibility of the data. As for accuracy in terms of future correlation with rain or snow fall, it is entirely possible that the environmental effect of the freezer is detrimental. However, Schaefer and others have shown some consistency in results which they have obtained and correlated. Nevertheless further research is necessary to ascertain the validity of these data. Both field work as well as laboratory work are required with this in mind.

In general, it was found that the snow crystal count increased somewhat logarithmically with decreasing temperatures. At $-30^{\circ}C$ the count ranged between 10^5 and 3×10^5 crystals per m^3 while at $-15^{\circ}C$ the range was approximately $7 \times$

10^3 to 10^5. The lower counts were generally found for fair days with high barometer and the high counts for rainy or cloudy days with a low barometer. The high count would possibly indicate that larger numbers of salt nuclei from the ocean were present when rain or cloudiness swept in from the west. A lower barometer should merely correlate with rainy or cloudy days as is usually the case in meteorological predictions.

Activation of Nuclei

The fact that the snow crystal count varies with temperature might indicate that the ice crystals form around the various types of nuclei which become activated at different temperatures. Schaefer et al. (11) point out the fact that ice crystallization does vary with temperature depending upon the type of material the nuclei are composed of, Thermodynamically, the water droplet should become more unstable with respect to the increased supercooling and therefore multiply the effect of various nuclei. This would substantiate some sort of logarithmic increase in crystal count with temperature decrease as indicated by the graphs. Because the ice crystal count may not indicate all of the nuclei present, it was felt that a more accurate nomenclature of the measurements made should be ice crystal count instead of nuclei count. Further work in the experimental methods of nuclei or crystal count as well as a more complete thermodynamic study of the phenomena is necessary to guide our thinking insofar as natural or artificial rain or snow fall is concerned.

From unplotted data by Schaefer (11) and data by Findeisen and Schulz (3) on the ice crystal count as a function of temperature, a comparison was made in Figure 9 with data obtained by the authors. The same general trend is shown but the orders of magnitude are quite different. This is possibly caused by the different geographical locations of the experiments. Schaefer's data however shows a plateau over a rather wide temperature range while the data of

Findeisen and Schulz agrees in shape with the authors' data. However Schaefer et al. (11) used a rough method of counting which more or less averaged the results. Findeisen and Schulz performed their experiments with a Wilson type expansion chamber which could be controlled insofar as the expansion velocity was concerned. They showed that the rate of expansion (or change in temperature with time) affects the results. That is, the reaction rate of ll crystal formations and the time allowed at a given temperature affects the crystal count. The authors' results may be higher because more time was allowed for the ice crystals to form.

During some of the tests, it was thought that some indication of the ice crystal formation mechanism might be detected by obtaining a count with both increasing and decreasing temperatures in the freezing chamber. It was found that the ice crystal count, as a function of temperature, was approximately the same in either case. This would indicate some sort of relation between the interchange of water between ice crystals and supercooled water droplets, particularly under the test conditions of air saturation with respect to water. Schaefer (12) noted that ice crystals were formed by direct condensation of vapor to the solid state at the expense of water from the water droplets. The results which are described above would agree with this surmise because of the decrease of ice crystals with increasing temperatures. However, other questions concerning this reaction could be posed, such as, is there a distinction between crystals which sublime with increasing temperatures and those that do not because of the nuclei?

Artificial Nucleation

It was felt that if the variation in counts were partially due to different types of nuclei being present an artificial addition of one type might cause a convex bump in the graphical plot of count versus temperature. A salt spray

was used as a means of increasing the salt nuclei and results of a subsequent count showed an increase in number of snow crystals with a suggestion of a bump. However, at the present time, not enough data have been taken to substantiate a conclusion.

Spark Discharge Effects

The formation of snow crystals, after a spark discharge, was well defined. No reference of this method had been previously found in the literature, thus leading the authors to make further preliminary investigations. In brief, the number of snow crystals visible at a given temperature increased many times after an electric spark discharge. It is possible that the formation of nuclei from the metal electrodes could have a partial effect as well as a change in electric charge on the water droplets. Figure 10 shows that each metal electrode did have a different effect on the snow crystal count. Metals such as copper, silver, magnesium, nickel and aluminum were used. With aluminum as electrodes, no appreciable effect could be noted. Little was done with respect to purity of metal or the variation of spark intensity. The spark was formed by discharging a bank of condensers which had been charged to 175 volts. Further investigation along these lines should yield valuable data concerning the fundamental nature of ice crystal formation. It is possible that electric storms operate in the same manner as was found in the freezer. Schaefer (10) (13) states that electrification may be a causitive agent or an end result. Thus it may be that rain or snow precipitation or the prevention of them may be triggered with artificial electrification. This could be caused by a discharge or even the passage of a charged aircraft through a cloud.

CONCLUSIONS

1. The number of snow crystals increased somewhat logarithmically with a decrease in temperature from 0°C to -34°C and became countless at approximately -39°C.

2. Practically no crystals were observed between 0 to -2°C.

3. Although actual snow crystal counts varied from day to day, the general shapes of the curves were similar. It was found that cloudy or rainy weather increased the count perceptibly.

4. An electric spark discharge in the freezer with natural nuclei present caused a definite increase in ice crystal count, at a given temperature, over the count obtained without a spark.

A SUGGESTED FUTURE PROGRAM

I. Validity of ice crystal count as a means of determining the effective nuclei.

- A. Thermodynamic examination of the system.
- B. Experimentation with a cold chamber and a Wilson type expansion chamber.
  1. Use of visual and photographic counting technique.
  2. Photo and electron microscopic examination of the nuclei and ice crystals.
- C. Relation between freezing, sublimation and condensation nuclei.
- D. Correlations from field tests.

II Nuclei counting by means of ice crystals at high altitudes from aircraft.

- A. Construction of an unrefrigerated Wilson type expansion chamber.
- B. Refrigerated devices.

III. Study of spark discharge or electrification on ice crystal formation.

- A. Use of different materials for electrodes.
- B. Use of various electric potentials.
- C. Photo and electron microscopic examination of the ice crystals formed.

LITERATURE CITED

1. Bentley, W. A. and Humphreys, W. J. "Snow Crystals", 1st Edition, McGraw-Hill Book Company, Inc., New York (1931).

2. Cwilong, B. M. "Sublimation in Wilson Chamber", Proc. Roy. Soc., Ser. A., 190, 137-143 (1947).

3. Findeisen, W. and Schulz, G. "Experimentelle Untersuchungen Übes die atmosphärischi Eisteilchenbildung, I" Forsch. Erfahr Der Reichs Wettered, Reihe A, Ne 27, Berlin (1944).

4. Fournier D'Albe, E. M., "Ice Nuclei in the Ultramicroscope and the Atmosphere" J. Glaciol. 1 310 (1949).

5. Heverly, J. R. "Supercooling and Crystallization" Trans. Amer. Geophys. Union 30,205 (1949).

6. Hoseler, C. L. "On the Crystallization of Supercooled Clouds" Journ. Meteor. 8, 326 (1951).

7. Houghton, H. G. "On the Physics of Clouds and Precipitation" Compend. of Meteor., Amer. Meteor. Soc., Boston, p 165 (1951).

8. Kumai, Motoi "Electron Microscope Study of Snow-Crystal Nuclei" Journ. of Meteor., 8, 151 (1951).

9. Ludlum, F. H. "The Physics of Ice Clouds and Mixed Clouds" Compend. of Meteor. Amer. Meteor. Soc., Boston, p 192 (1951); also "Forms of Ice Clouds" Quart. J. of Research of Meteor. Soc., 74, 39 (1948).

10. Schaefer, V. J. "Properties of Particles of Snow and the Electrical Effects they Produce in Storms" Trans. Amer. Geophys. Union, 28, 587 (1947).

11. Schaefer, V. J. et al. "Final Report on Project Cirrus", G. E. Research Laboratory Contract No. W-36-039-SC-324 27, Report No. RL140, December 31, 1948.

12. Schaefer, V. J. "The Detection of Ice Nuclei in the Free Atmosphere" J. Meteor. 6, 283 (1949).

13. Schaefer, V. J. "Snow and its Relationship to Experimental Meteorology" Compendium of Meteorology, Amer. Meteor. Soc., Boston, Mass, (1951) pp 221-234.

14. Vonnegut, B. "Production of Ice Crystals by the Adiabatic Expansion of Gas" J. Appl. Phys. 19, 959 (1948).

15. Vonnegut, B. "Nucleation of Supercooled Clouds by Silver Iodide Smokes" Chem. Rev. 44, 277-289 (1949).

16. Weickmann, H. "Die Eisephase in dar Atmosphäre" Ber. dtsch Wetterd. U. S. Zone Nr 6 54SS (1949).

ADDITIONAL REFERENCES

Aitken, J. "Collected Scientific Papers", Cambridge University Press, 1923.

Bergeron, T. "On the Physics of Cloud and Precipitation", P. V. Meteor. Un. Geod., Geod. Geophys, Int., PT. 2, pp 56-178, (1935).

Bergeron, T. "The Problem of Artificial Control of Rainfall on the Globe, Part I, General Effects of Ice-Nuclei in Clouds" Tellus, vol I, No. 1, pp 32-43 (1949).

Coons, R. D. and Others, "First Partial Report on the Artificial Production of Precipitation - Stratiform Clouds - Ohio 1948", Bull. Amer. Meteor. Soc. 29 266, (1948).

Coons, R. D. and Others "Second Partial Report on the Artificial Production of Precipitation - Cumuliform Clouds - Ohio 1948", Bull. Amer. Meteor. Soc., 29, 544 (1948).

Coons, R. D. and Others "Third Partial Report on the Artificial Production of Precipitation - Orthographic Stratiform Clouds - California, 1949", Bull. Amer. Meteor. Soc., 30, 255 (1949).

Coons, R. D. and Others "Fourth Partial Report on the Artificial Production of Precipitation - Cumulus Clouds - Gulf States, 1949", Bull. Amer. Meteor. Soc., 30, 289 (1949).

Fournier D'Albe, E. M. "Some Experiments on the Condensation of Water Vapor at Temperatures Below 0°C" Quart. J. Roy. Meteor. Soc. 75, 1 (1949).

Junge, Christian "Nuclei of Atmospheric Condensation" (Transl. from German) Compendium of Meteor., Amer. Meteor. Soc., Boston, Mass. (1951) p 182.

Landsberg, H. "Atmospheric Condensation Nuclei", Beitr. Geophys: (Suppl.) 3, 155 (1938).

Langmuir, I. "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures above Freezing", J. Meteor., 5, 175 (1948).

Ludlam, F. H. "The Physics of Ice Clouds and Mixed Clouds", Compend. of Meteor., Amer. Meteor. Soc., Boston, Mass. (1951) pp 192-198.

Moller, Fritz "Thermodynamics of Clouds" Compend. of Meteor., Amer. Meteor. Soc., Boston 199 (1951).

Nakaya, U. and Others "Preliminary Experiments on the Artificial Production of Snow Crystals" J. Fac. Sci., Hokkaido University Ser. 2, 2 1-11 (1938).

Nakaya, U. et al. "Further Experiments on the Artificial Production of Snow Crystals", J. Fac. Sci., Hokkaido University, Ser. 2, 2, 13-57 (1938).

Nakaya, U. "The Formation of Ice Crystals" Compendium of Meteor., Amer. Meteor. Soc., Boston, Mass. (1951) p 207.

Palmer, H. P. "Natural Ice Particle Nuclei", Quart. J. Roy. Meteor. Soc. 75, 15 (1949).

Schaefer, V. J. "A Method for Making Snowflake Replicas", Science, 93, 239 (1941).

Schaefer V. J. "Occasional Reports No. 1-33," G. E. Research Laboratory, Schenectady, N. Y., Contract Nos. W-36-039-SC-38141 and DA-36-039-SC-15345.

Stickley, A. R. "An Evaluation of the Bergeron-Findeisen Precipitation Theory" Mon. Wea. Rev. 68, 272 (1940).

Woodcock, A. H. "Sampling Atmospheric Sea-Salt Nuclei over the Ocean", J. Mar. Res. 8, 177 (1949).

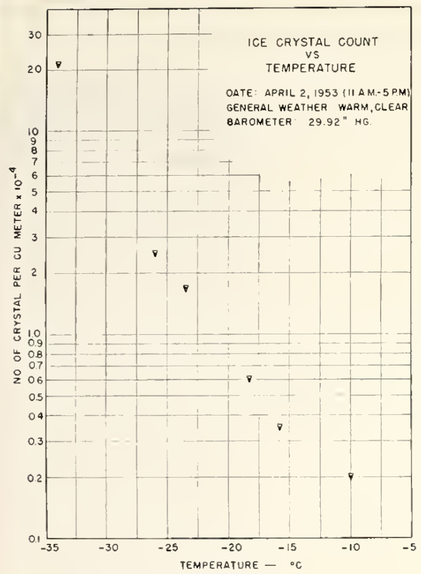

FIG 1

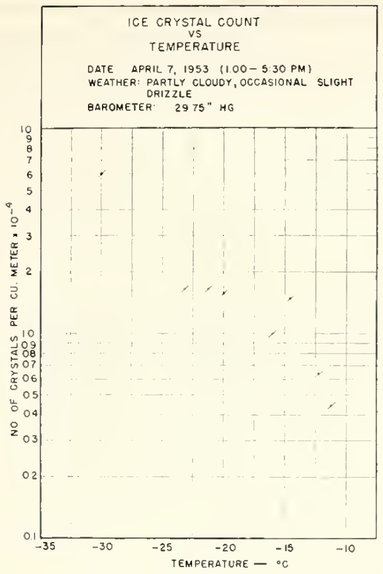
ICE CRYSTAL COUNT
VS
TEMPERATURE
DATE APRIL 7, 1953 (1:00 – 5:30 PM)
WEATHER: PARTLY CLOUDY, OCCASIONAL SLIGHT DRIZZLE
BAROMETER 29.75" HG
NO. OF CRYSTALS PER CU. METER x 10⁻⁴
TEMPERATURE — °C

FIG 2

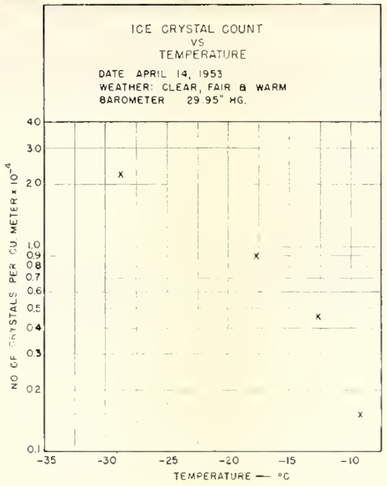

FIG 3

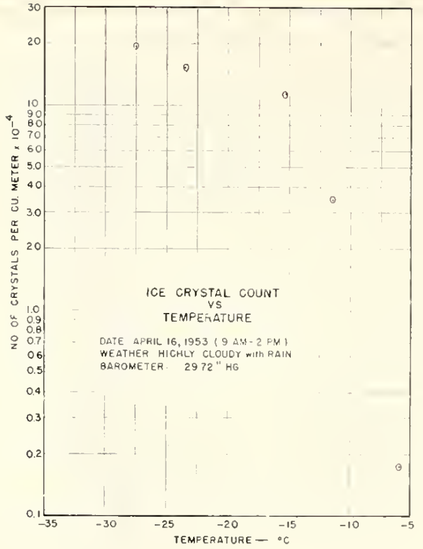

FIG 4

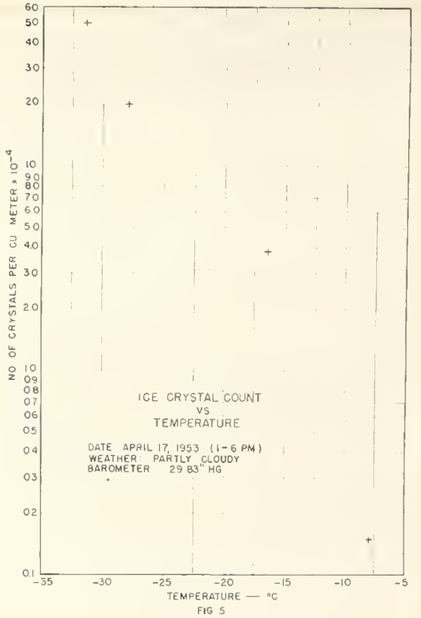

FIG 5

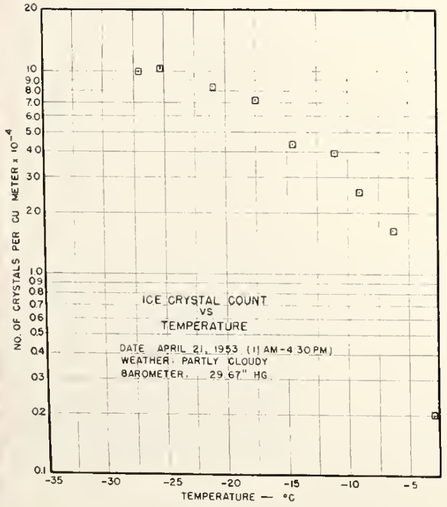

FIG 6

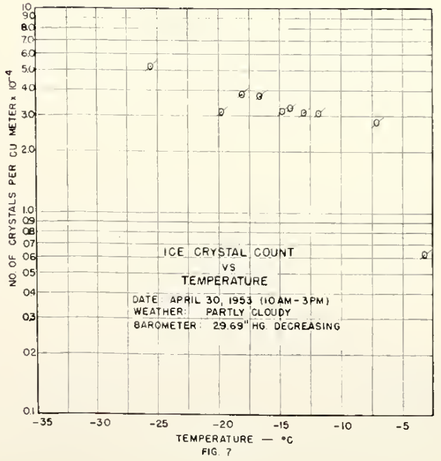

FIG 7

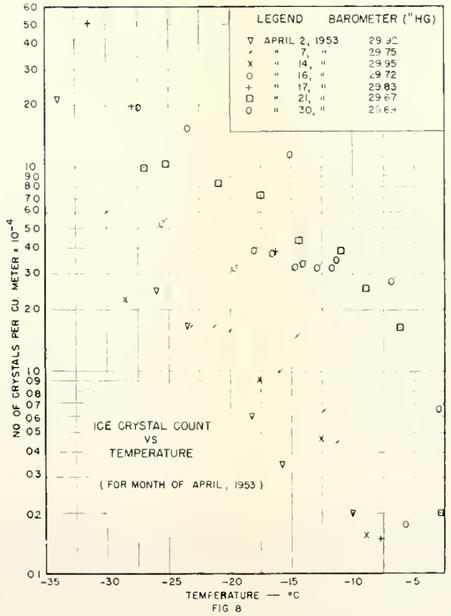
LEGEND BAROMETER ("HG)
▽ APRIL 2, 1953 29.92
△ " 7, " 29.75
X " 14, " 29.95
O " 16, " 29.72
+ " 17, " 29.83
□ " 21, " 29.67
◇ " 30, " 29.69
ICE CRYSTAL COUNT
VS
TEMPERATURE
(FOR MONTH OF APRIL, 1953)
NO. OF CRYSTALS PER CU. METER x 10⁻⁴
TEMPERATURE — °C

FIG 8

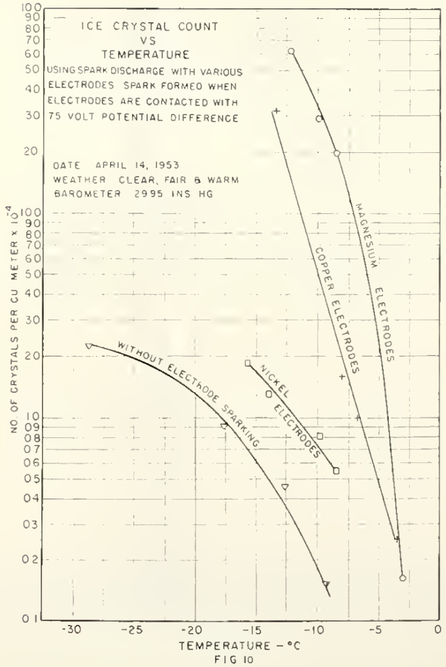
ICE CRYSTAL COUNT
VS
TEMPERATURE
USING SPARK DISCHARGE WITH VARIOUS ELECTRODES SPARK FORMED WHEN ELECTRODES ARE CONTACTED WITH 75 VOLT POTENTIAL DIFFERENCE
DATE APRIL 14, 1953
WEATHER CLEAR, FAIR & WARM
BAROMETER 29.95 INS HG
WITHOUT ELECTRODE SPARKING
NICKEL ELECTRODES
COPPER ELECTRODES
MAGNESIUM ELECTRODES
NO. OF CRYSTALS PER CU. METER x 10⁻⁴
TEMPERATURE – °C

FIG 10

COMPARISON WITH PUBLISHED DATA

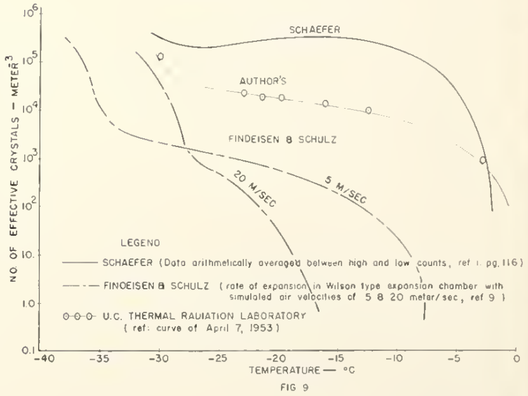
SCHAEFER
AUTHOR'S
FINDEISEN & SCHULZ
20 M/SEC
5 M/SEC
NO. OF EFFECTIVE CRYSTALS – METER³
LEGEND
SCHAEFER (Data arithmetically averaged between high and low counts, ref 1, pg. 116)
FINDEISEN & SCHULZ (rate of expansion in Wilson type expansion chamber with simulated air velocities of 5 & 20 meter/sec, ref 9)
O-O-O U.C. THERMAL RADIATION LABORATORY (ref: curve of April 7, 1953)
TEMPERATURE — °C

FIG 9

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

FIGURES FOR APPENDIX G

APPENDIX H

LEGAL REPORT

ON

LIABILITIES INVOLVED IN CREATION OF

ARTIFICIAL RAINFALL AND

POWERS OF THE STATE TO REGULATE THE SAME

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Division of Water Resources

August, 1950, and
November, 1953

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ON
LIABILITIES INVOLVED IN CREATION OF ARTIFICIAL RAIN-
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LEGAL REPORT
ON
LIABILITIES INVOLVED IN CREATION OF ARTIFICAL RAIN-FALL AND POWERS OF THE STATE TO REGULATE THE SAME

The following progress report is submitted in response to a request by the State Water Resources Board for a report upon the responsibilities and liabilities involved in the creation of rainfall by artificial means and the power of the State to regulate and control such activities.

In order to determine the possible liabilities of one who causes precipitation of rainfall by artificial means it is necessary to first consider what rights, if any, might be adversely affected. This in turn involves a determination of the existence, nature and scope of private rights of ownership or use in the air and in water contained in the air, and possible remedies for any invasion of such rights.

There are no direct legal precedents which supply the answer to any of the above mentioned questions or to numerous other subsidiary problems that will doubtless arise as soon as the occasion presents itself. It is plain that the final answers can be supplied only by the Supreme Court, and by it only as each question is presented for decision in the light of particular facts and circumstances, and in view of such legislation as might be deemed advisable. Undoubtedly the opinions and conclusions of persons trained in the law will differ radically concerning the correct answers to the problems referred to, as they have previously differed whenever novel and untried situations have

arisen. Conclusions reached even after an exhaustive and time-consuming study, would of necessity be largely tentative. Dogmatic or positive opinions would be futile and misleading.

The relatively short period of time that has elapsed since this study has been initiated has not permitted an exploration of all of the legal aspects of the problem, nor has there been an opportunity as yet to give each authority cited that careful and detailed analysis of the law and facts involved that is required for a proper evaluation of its effect upon the questions to be considered. This progress report is submitted for the purpose of indicating the extent the study of the subject matter has progressed and the tentative conclusions which the study so far conducted appears to warrant.

In the light of this preliminary statement, the subject is discussed under the following headings: I. The Right of a Landowner in Natural Rainfall; II. Nature and Scope of the Right in Natural Rainfall; III. The Liabilities of an Artificial Precipitator; IV. Public Participation and Liability Therefor; and V. Regulation.

I. THE RIGHT OF A LANDOWNER IN NATURAL RAINFALL

All presently contemplated methods to artificially induce rainfall involve the capture of moisture which is naturally in the atmosphere by condensation of such moisture into water, ice or snow and the precipitation of such products by the natural force of gravity upon the land below. No method has been suggested of adding moisture to the air that does not naturally exist therein. It has been held that the air and all that is contained

therein is common property and not the subject of private ownership.[1] If so, then anyone who is able has a right to take and appropriate moisture contained in the air to his own use unless by so doing he interferes with a right of someone else, not of ownership, but of use in and to such moisture. Therefore our primary question is, "Has the owner of land any legal right in and to the natural moisture contained in the atmosphere and if so, what is the nature and extent of such right?"

No direct and positive answer to the above stated question is found in either court decisions, legal texts or statutes, for the simple reason that no one has ever either asserted the right to appropriate natural airborne water or has found the physical means to do so, at least until very recently. For this reason the right under examination has never been defined or even expressly recognized.

However, it is true that, in addition to protecting the land from actual physical damage as a result of conditions created upon adjoining land, whenever the soil has been threatened with deprivation of those essential natural advantages without which it would lose its very character and potentialities of use, the common law has evolved means of protecting it and has forbidden an interference with such natural advantages by others. Thus, certain so-called "natural rights" have been recognized. Such natural rights are recognized by law because without them there would be no security in the enjoyment of land by its owner. They are inherent in the land ex jure naturale. Without them a neighbor

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1/ Hinman v. Pacific Air Transport (1936), 84 Fed.2d 755 (cert. denied, 57 Sup. Ct. 431).

might deprive a landowner of the benefits derivable from things which in the course of nature are available for the common good of all, and which the law wisely provides shall not be wrested from one by the act of another.1/

"Pure air, the right of support, the benefits from flowing water, all such intangible ingredients, mixing together with the soil itself, join to form the value or quality of the estate owing to its natural position; their preservation maintains the use of the land. They are all 'natural rights' in the sense that they are an essential part of the value of the estate in its natural condition." 2/

We find that though previously recognized natural rights such as the right to have air diffused over one's premises in approximately its natural condition, free from pollution by smoke, dust or vapors, 3/ the right to freedom from disturbance by unreasonable noise or vibration 4/ and excessive and unreasonable heat, 5/ the right of riparian land to the natural flow of water, 6/ the right of overlying owners to underground water, 7/ the right of drainage and the right of support, may all be distinguished in some respects both from each other and from a right to receive and use moisture naturally supplied to land from the air, still these rights all have one thing in common. They are necessary to the full enjoyment of the land in its natural state and

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1/ Gray v. McWilliams, 98 Cal. 157, 32 Pac. 976.
2/ Wiel - Water Rights, Third Edition, p. 774.
3/ Sullivan v. Royer, 72 Cal. 248, 13 Pac. 655.
4/ McGrath v. Basich Bros. Construction Co., 7 Cal. App.2d 573, 46 Pac.2d 981.
5/ Vaughan v. Bridgham, 193 Mass. 392, 79 N.E. 739.
6/ Turner v. James Canal Co., 155 Cal. 82, 99 Pac. 520.
7/ Katz v. Walkinshaw, 141 Cal. 116, 74 Pac. 766.

with the advantages supplied by nature, and without them the normal and reasonable use and enjoyment of the land would be severely impaired or completely destroyed. That is to say, the impelling reason for their recognition, preservation and protection is identical.

The right to receive water from whatever source it may be supplied to land by natural means has been heretofore recognized and affirmed in principle whenever its destruction or material impairment has been threatened. Previous decisions have been concerned with the right of the landowner to receive and use water from surface streams and other bodies of water and from underground sources. Just as the reasons for recognizing all natural rights apply to the right to receive and use airborne water, so do the reasons for recognizing and protecting the natural right to receive and use water from streams and underground sources apply with equal force and logic to the right of land to receive water supplied to it through the air under natural conditions.

We also find that in sustaining the existence of a "natural" riparian right to water flowing in a stream, the courts have upon occasion resorted to the analogy of the right of a landowner to the free passage of unpolluted air. Thus, it has been said that "the right to running water has always been properly described as a natural right, just like the right to the air we breathe; they are the gifts of nature and no one has the right to appropriate them."1/ Throughout all of the early English cases which define the basis for a riparian right runs the concept of

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1/ Chasemore v. Richards, 7 H.L. Cas. 349, 11 Eng. reprint 140.

physical contact between land and water, and this basis for the right has been accepted generally in this country, "hence it follows that whether or not a person is the owner of riparian rights depends entirely upon the fact as to whether or not he owns land which is contiguous to and touches upon the water." 1/ The basis of the right to water supplied to land by nature has been strictly defined by our own courts. Speaking of a riparian right to water in surface streams, it has been well stated that it "comes from the situation of the land with respect to the water, the opportunity afforded thereby to divert and use the water upon the land, the natural advantages and benefits resulting from the relative positions, and the presumption that the owner of the land acquired it with a view to the use and enjoyment of these opportunities, advantages and benefits." 2/ This idea that the riparian right is a natural one in the sense of being made up of all of these intangible benefits and advantages runs through all of the better opinions on the subject. 3/

All land is situated with respect to the rainfall which naturally falls upon it in much the same manner as riparian land is situated with respect to streams and other bodies of water; that is, the land and the water come into physical contact either as the water stands in pools or moves by or through the land in streams or falls from the clouds onto the land.

1/ Kinney on Irrigation and Water Rights, Second Edition, Vol. 1, Sec. 451, p. 761.
2/ Turner v. James Canal Co., 155 Cal. 82, 99 Pac. 520.
3/ Wiel - Water Rights, Third Edition, p. 775.

"The opportunity afforded thereby to divert and use the water on the land" is at least equal in the case of rainfall, with the distinction that a diversion by artificial means of the water which is in physical contact with the land in order to use it upon the land is generally not necessary in the case of rainfall since the land receives its benefit therefrom entirely by natural processes.

"The natural advantages and benefits resulting from the relative positions" collectively form the real basis for the recognition of all natural rights as we have seen, and it is unnecessary to dwell upon the similarity of natural benefits received from rainfall and those received from other sources of water by way of seepage and overflow. "The presumption that the owner of land acquired it with a view to the use and enjoyment of these opportunities, advantages and benefits" is as reasonable in one case as the other.

It is believed that these considerations should be given weight in determining whether there is a natural right on the part of every landowner to receive water in the air which is supplied to his land by natural means. 1/

Of course rainfall, although it comes in contact with the land, does so at irregular and largely unpredictable intervals. This is universally true, but emphatically so in the arid and semi-arid west. Its source of supply is not stationary and permanently fixed as in the case of lakes and streams, but is a movable, fleeting and comparatively nebulous cloud or mass of vapor floating

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1/ See 1 Stan. L. Rev., 43, "Who Owns the Clouds", for an excellent discussion, concluding that a natural right to rainfall does exist.

in the air at the mercy of the wind, atmospheric pressure and temperature changes and other vagaries of nature. Will the recognition of the natural right to rainfall be affected by these distinctions? If the basis of the rights is the same it does not seem that these matters would be of controlling importance. Actually the primary and original source of practically all fresh water is rainfall, whether it falls on and is absorbed in remote land to reappear upon the surface and flow by gravity past other lands, or whether it falls directly upon the latter lands in the first instance. If artificial precipitation were to result in causing springs and streams to dry up, it would amount to a diversion of water in which riparian lands have a natural right as much as though an upper appropriator had built a dam across the stream with the same effect. The whole evaporation - precipitation - flowing cycle is a continuous and single process. It matters little at what point in the cycle water is interrupted or diverted so far as the person entitled to its use is concerned. This line of reasoning, if sound, might lead to the conclusion that the right to natural rainfall is a more primary and direct natural right than is the right to water in streams, lakes and underground sources.

II. NATURE AND SCOPE OF THE RIGHT IN NATURAL RAINFALL

The basis of a natural right which is relied upon for establishing its existence also necessarily defines and limits that right. If the basis is physical contact and the natural advantages resulting therefrom, then the right extends to all water thus coming in contact with the land by natural means, but only to

such water. In other words, the right extends only to rain which falls naturally upon the land and does not extend to all water contained in clouds. Clouds are merely the source of supply and there can be no natural right to a source of supply unless water from it naturally reaches the land. Just as a landowner has no riparian right in stream water which in the course of nature if unobstructed would not reach his land, 1/ so he can have no right to celestial water so long as it remains in a cloud and does not come in contact with the land by natural means nor give any benefit or advantage to the land. It follows that the right of a landowner, if any, is in natural rainfall and not in clouds, except as the latter constitute a source of supply for natural rainfall upon his land. Assuming that a landowner does have a right to receive and use rainfall, the next question encountered is the nature and scope of the right. An attempt to forecast what decision would be reached by the courts if this problem were presented to them for consideration and determination, leads somewhat further into the realm of conjecuture and speculation. However, some general principles may be stated which have been held to be applicable to the natural right to receive water from surface streams and underground supplies and which it is believed might properly be held to be equally applicable to water received from the air.

Generally speaking, natural rights do not enable a person entitled to their benefit to object to activities by others so long as the right of enjoyment and use inherent in the ownership of land is not materially affected. Thus, a riparian owner may

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1/ Duckworth v. Watsonville, etc. Co., 150 Cal. 520, 89 Pac. 338.

not prevent the use of water in a stream to which his land is riparian by an upper owner so long as it is returned to the natural channel of the stream above his land. 1/ Also as noted previously, one may not object to the use of water which in a state of nature would not flow to his land. 2/ Only the right to use water, and not the corpus of water, is subject to private ownership. 3/ A person entitled to the use of water has no grounds for complaint so long as he receives the quantity of water which nature supplied to him. The substitution of artificial for natural means 4/ or source 5/ of supply does not give rise to a cause of action so long as no substantial injury results to the usufructuary right.

The right to the use of water in California has been materially modified by the adoption of Article 14, Section 3, of the California Constitution. Although it may be argued that the people of the State did not have in mind rainfall when they adopted the provisions of this section, the fact remains that the reference contained therein is to all water and that water from all sources, including rainfall, is within both the purpose and object of the law, to wit, conservation and beneficial use of all of the water resources of the State to the fullest extent of which they are capable and prevention of waste of water in the interest of the people and for the public welfare. These constitutional

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1/ Vernon Irr. Co. v. City of Los Angeles, 106 Cal.237, 39 Pac. 762.
2/ Duckworth v. Watsonville et. Co., 150 Cal. 520, 89 Pac. 338.
3/ Rancho Santa Marguerita v. Vail, 11 Cal.2d 501, 81 Pac.2d 533.
4/ Crum v. Mt. Shasta Power Corp., 117 Cal. App. 586, 4 Pac.2d 564.
5/ 67 C. J., Waters, p. 1018, Sec. 445

mandates apply to the use of all water and override laws and decisions inconsistent therewith. 1/

It is now established law in this State that all rights to the present use of water, including a riparian right, extend only insofar as the water is actually put to a beneficial use. However, natural rights to the use of water are not lost by non use and have a prospective character. Although one entitled to a natural right to the use of water may only assert it to the extent he is prepared to put it to a beneficial use, he is not limited to the quantity of water beneficially used by him in the past and may assert the right at any time in the future unless prescriptive rights have been acquired against him. 2/ It follows that a landowner would have no right to complain of the use of potential rain water by others which he was not using beneficially on his land or which he has allowed to waste.

Water which constitutes a source of common supply for two or more users must be apportioned equitably between them when the supply is insufficient to satisfy the reasonable needs of all. This has long been the law relating to the right of one riparian owner against another because they all have equal access to the water by reason of their natural relative positions, 3/ and the same rule has been applied to the right to use underground water. 4/ It has been suggested that this principle should be applied to water contained in the air and that the owner of land over which a

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1/ Peabody v. City of Vallejo, 2 Cal.2d 531, 40 Pac.2d 486; Chow v. City of Santa Barbara, 217 Cal. 673, 22 Pac.2d 5.
2/ Peabody v. City of Vallejo, supra.
3/ Hudson v. Dailey, 156 Cal. 617, 105 Pac. 748.
4/ Katz v. Walkinshaw, 141 Cal. 116, 74 Pac. 766.

cloud passes may intercept a reasonable portion of such water and thus prevent it to that extent from reaching the land on which it would fall in the course of nature. 1/ However, the reasons for recognition of correlative rights to water do not seem to apply to this situation. Such rights have been heretofore recognized only as between riparian or overlying owners each of whom have an equal natural right to a common supply of water by reason of their collectively exclusive right of access to the supply. Landowners do not have an exclusive right of access to clouds, nor, as we have seen, do they have any natural right to water contained in clouds (except to the extent such water is precipitated by natural means upon their land). Since the basis for the doctrine of correlative rights does not apply, it seems reasonable to suppose that each landowner has an absolute right as against others to receive all of the rain naturally precipitated upon his land except as modified and limited by the principles previously set forth under this heading.

III. THE LIABILITIES OF AN ARTIFICIAL PRECIPITATOR

Liabilities that might be incurred by one engaging in the artificial precipitation of rain may be assumed to fall generally into two classes: (1) liability to a landowner for wrongful "diversion" of the water to which a prior right has attached, and (2) liability for damage to persons and property.

A. Liability for Diversion of Water

The following discussion assumes that there are rights in and to the use of natural rainfall:

1/ See Opinion of L. A. County Counsel printed in L. A. Daily Journal, Mar. 29-31, 1948.

All rights to the use of water are entitled to the protection of the courts at law or in equity. When there is no substantial infringement of the right by a material diminution of the supply by reason of the exercise of the subsequent right, the owner of the paramount right is restricted to a judgment declaring his preferential and paramount right and enjoining the assertion of an adverse use which might otherwise ripen into a prescriptive right. 1/

If the exercise of the subsequent right causes a substantial diminution of the supply, the owner is entitled to injunctive relief unless a public use has attached to the subsequent right, and in any event, he is entitled to compensation. 2/ The market value of the land with and without the water right is the measure of damages to land for violation of a riparian right to the natural flow of water. 3/

It is believed that the foregoing principles would limit the relief available to the owner of rights in the use of natural rainfall. That is to say, the substantial diminution of the water supply that he would otherwise receive but for the artificial precipitation of water contained in the air to the extent that such water was being beneficially used by him on the land, might be enjoined unless a public use had intervened, in which case he would be entitled to compensation for the taking of

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1/ Peabody v. City of Vallejo, 2 Cal.2d 351, 40 Pac.2d 486; City of San Bernardino v. Riverside, 186 Cal. 7, 198 Pac. 784.
2/ Peabody v. City of Vallejo, supra; Hillside Water Co. v. L. A., 10 Cal.2d 677, 76 Pac.2d 681.
3/ Seneca v. Consol. Gold Mines Co. v. Great Western Power Co., 209 Cal. 206, 287 Pac. 93.

private property for a public use. Beyond this he would have no right to relief other than a judgment declaring his preferential and paramount right and enjoining the assertion of an adverse right.

B. Liability for Damage.

Turning now to the question of the right to recover damages for physical injury to person or property, we will assume a situation where damage results directly from the artificial precipitation of water, as by flood or storm waters produced by such precipitation.

At common law, damage to real property as the result of the activity of others was divided into two classes: direct trespass resulting in liability without proof of intent or negligence and indirect trespass as where a defendant obstructed or diverted a stream of water so that the water ultimately flowed upon plaintiff's land, in which case proof of either intent or negligence was a prerequisite to the recovery of damages. 1/ These distinctions still persist in some jurisdictions, although the modern and better rule is that proof of intent or negligence is required without regard to whether the trespass is direct or indirect except where the actor is engaged in extra hazardous activity. 2/

However, in some situations the rule has been applied that the injury itself may be sufficient evidence of negligence. For example, a rice grower has been held liable for damage caused to adjoining land by reason of water percolating from his fields. 3/

1/ Prosser on Torts, pp. 79-80.
2/ Restatement of Torts, Sec. 166.
3/ Kall v. Carruthers, 59 Cal. App. 555, 211 Pac. 43. Cf. Nelson v. Robinson, 47 Cal.App.2d 520, 118 Pac.2d 350.

The cited decision discusses the basis for liability for damage to land caused by the artificial use of adjoining land and calls attention to the fact that such liability has at various times been declared to be based upon the theory of nuisance or absolute liability or negligence, but that in a case of this kind the injury itself may be sufficient proof of negligence. We quote from the opinion as follows:

> "The liability of the water to do injury if allowed to escape must be continually borne in mind by the one attempting to make artificial use of it, and his failure to bear that fact in mind may be material upon the question of his liability.
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> * * *
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> "It will be noted in the decisions of our own state that the old maxim, 'So use your own as not to injure another's property,' has been so often approved in cases similar to the one at bar, and such cases have been decided by this maxim so many times, that the maxim should be decisive of this case.
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> * * *
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> "Under the subject of Nuisances, Judge Cooley, in his work on Torts, says:
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> "'If the water is so raised that by percolation the land of another is injured, the party raising it is responsible, not because he has unreasonably, negligently, intentionally, or unexpectedly flowed the land of another for his own benefit, but because he has done it in fact. The right of one to be secure against the undermining of his buildings by water, or the destruction of his crops, or the poisoning of the air by the stealthy attacks of an unseen element, is as complete as his right to be protected against open personal assaults or the more demonstrative but not more destructive, trespass of animals.'
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> * * *
>
> "Section 3479 of the Civil Code of the state of California declares, among other things, that 'an obstruction to the free use of property, so as to interfere with the comfortable enjoyment of life or property,' is a nuisance."

It thus appears where damage results to another from the use of water in an unnatural or artificial manner, the injured party must be made whole and that whether his remedy be predicated upon absolute liability, presumed negligence or nuisance, the result is the same by giving effect to the maxim "So use your own as not to injure others' property" which finds expression in our Civil Code, Section 3514.

We turn now to the exception to the requirement of intent or negligence in case of extra hazardous activities as set forth in the restatement. 1/ The most classic example of such activity is blasting and one which has received the frequent attention of the courts. Many decisions impose liability for damage caused by the use of explosives as well as for damage caused by other hazardous acts by classifying them as nuisances per se. 2/ Thus the doctrine of Fletcher v. Rylands, L. R. 1 EX 265 is widely recognized in effect even where not in name. That doctrine imposes strict liability without regard to negligence for injury caused by the escape of anything kept upon one's land which is of a nature to do mischief in case it escapes. (Later limited to "non-natural" use of land.) This rule was at first rejected in this country as being unsuited to a pioneer and expanding civilization where new and untried enterprises should be encouraged. This attitude has now been generally replaced by the view that the hazardous enterprise, however socially valuable,

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1/ Restatement of Torts, Sec. 166.
2/ Prosser, on Torts, p. 452; Alonzo v. Hills, 95 Cal. App. 2d____, 214 Pac.2d 50.

must pay its way and make good the damage inflicted. 1/ The doctrine has apparently been accepted by a number of California decisions. 2/

Some decisions have announced that blasting in a place properly selected and protected is not a nuisance per se, 3/ but if injury occurs it is nevertheless a sufficient basis upon which to predicate liability where the act was the sole and proximate cause of the injury. 4/

It has been said that blasting in a populous place may constitute an ultra-hazardous activity accompanied by strict liability but that the same act performed in remote places where there is little danger of injury is not considered as a "nuisance per se" and not actionable in the absence of negligence or tortious intent. 5/ Other cases have apparently applied the rule of strict liability without regard to the character of the neighborhood. 6/ In any event, the basis of the rule imposing strict liability is the undue risk notwithstanding all reasonable precautions, 7/ and it would seem that the character of the neighborhood would be one factor to take into consideration in determining whether the risk was undue or reasonable. It has been suggested that an injury caused by blasting may not be actionable in the

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1/ Prosser on Torts, p. 451
2/ See Rozewski v. Simpson, 9 Cal.2d 515, 71 Pac.2d 72.
3/ McGrath v. Basich Bros. Construction Co., 7 Cal. App.2d, 573, 46 Pac.2d 981; Houghton v. Loma Preita Lumber Co., 152 Cal. 500, 93 Pac. 82.
4/ McGrath v. Basich Bros. Construction Co., supra; Nola v. Orlando, 119 Cal. App. 518, 6 Pac.2d 984.
5/ Alonzo v. Hills, 95 Cal. App.2d ___, 214 Pac.2d 50; Prosser on Torts, p. 448.
6/ McGrath v. Basich Bros. Construction Co., 7 Cal. App.2d 573, 46 Pac.2d 981.
7/ Prosser on Torts, p. 447.

absence of negligence, if its necessity or utility is so great as to justify reasonable risk. 1/ The general rule has been applied to blasting cases that a primary cause may be the proximate cause of the injury although it operates through successive agencies to effect the final result. 2/ The fact that the explosives were being lawfully used under the authority of the State does not excuse the user from his duty to so use his own rights as not to infringe upon those of others and, of course, whether the tort feasor is a landowner or not is entirely immaterial since liability is determined by the effect of the instrumentality. 3/

Although the use of explosives is the most common example of an extra-hazardous activity, there are many others. Aviation is still generally classified as such an activity, imposing strict liability for injury caused regardless of intent or negligence. 4/

The important and often cited case of Green v. General Petroleum Corp., 205 Cal. 328, 270 Pac. 952, involved oil well drilling operations by defendant upon adjoining property. The effect was to cover plaintiff's property with oil, gas, mud and rocks, resulting in serious damage. The court found that although the gas was penetrated at a higher level than the defendant had reason to anticipate, the fact remained that the intentional drilling of the well, an enterprise lawful in itself, was the direct

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1/ Alonzo v. Hills, supra.
2/ Peterson v. General Geophysical Co., 81 Cal. App. 2d ____, 185 Pac.2d 56.
3/ McGrath v. Basich Bros. Construction Co., 7 Cal. App.2d 573, 46 Pac.2d 981.
4/ Uniform aeronautics Act, Sec. 5; Restatement of Torts, Sec. 165; Rochester Gas & Electric Co. v. Dunlop, 266 N.Y.S. 469.

and proximate cause of the gas blow-out and that the resulting damage was as much the direct and proximate consequence of the sinking of the well as if the gas had been intentionally liberated. The following quotation from the opinion is instructive:

> "The well brought to the surface of the earth an uncontrollable element, productive of injury to property located in proximity to the drilling operations carried on by the appellant * * * That an injury may exist without liability under some circumstances is certain. But such a result is contrary to the general rule of liability * * *.
>
> "* * * The present case does not arise from either the conduct of a nuisance per se, or from an inevitable calamity or act of God, but presents a situation to which the doctrine of 'sic utere tuo ut alienum non laedas' may be applied in its broad and fundamental import. That ancient maxim of jurisprudence is incorporated, in substance, in the statutory law of this State. The Civil Code provides (section 3514):
>
> "'One must so use his own rights as not to infringe upon the rights of another.'
>
> "Where one, in the conduct and maintenance of an enterprise lawful and proper in itself, deliberately does an act under known conditions, and, with knowledge that injury may result to another, proceeds, and injury is done to the other as the direct and proximate consequence of the act, however carefully done, the one who does the act and causes the injury should, in all fairness, be required to compensate the other for the damage done. The instant case offers a most excellent example of an actual invasion of the property of one person through the act of another. The fact that the act resulting in the 'blow-out' was lawful, and not negligently done, does not, in our opinion, make the covering of respondents' property with oil, sand, mud, and rocks any less an actual invasion of and a trespass upon the premises.
>
> "It ought to be, and we are of the view that it is, the rule that, where an injury arises out of, or is caused directly and proximately by the contemplated act or thing in question, without the interposition of any external or independent agency which was not or could not be forseen, there is an absolute liability for the consequential damage, regardless of any element of negligence either in the doing of the act or in the construction, use, or maintenance of the object or instrumentality that may have caused the injury. In our judgment no other legal construction can be placed upon the operations of the

appellant in this case than that, by its deliberate act of boring its wells, it undertook the burden and responsibility of controlling and confining whatever force or power it uncovered. Any other construction would permit one owner, under like circumstances, to use the land of another for his own purpose and benefit, without making compensation for such use. We do not conceive that to be the law."

In the recent case of Luthringer v. Moore, 31 Cal. 2d 489, 190 Pac. 2d 1, the whole subject of ultra-hazardous activities and the rights and liabilities of the parties in connection therewith received a detailed discussion by the Supreme Court of California. Preliminarily the opinion states that the question of whether the occasion was a proper one for imposing absolute or strict liability is one of law for the court to decide. The court then determines that the activity of the defendant in releasing cyanic acid gas in the basement of a commercial building where there were a great many tenants was an extra-hazardous activity calling for liability without fault. In support of this holding the opinion quotes at length from the Restatement of Torts, Section 519 and 520, as follows:

"'One who carries on an ultra-hazardous activity is liable to another whose person, land or chattels the actor should recognize as likely to be harmed by the unpreventable miscarriage of the activity for harm resulting thereto from that which makes the activity ultra-hazardous, although the utmost care is exercised to prevent the harm. * * * An activity is ultra-hazardous if it (a) necessarily involves a risk of serious harm to the person, land or chattels of others which cannot be eliminated by the exercise of the utmost care, and (b) is not a matter of common usage. * * * An activity is a matter of common usage if it is customarily carried on by the great mass of mankind or by many people in the community. It does not cease to be so because it is carried on for a purpose peculiar to the individual who carries it on."

"* * * the manufacture, storage, transportation and use of high explosives, although necessary to the construction of many public and private works, are

carried on by a comparatively small number of persons and, therefore, are not matters of common usage. So, too, the very nature of oil lands and the essential interest of the public in the production of oil require that oil wells be drilled, but the dangers incident thereto are characteristic of oil lands and not of lands in general * * *"

The opinion further states that whether the doctrine of Fletcher v. Rylands is in effect in California or not, the case of Green v. General Petroleum Corp. 1/ enunciated a rule of absolute liability in such a situation. "The important factor is that certain activities under certain conditions may be so hazardous to the public generally, and of such relative infrequent occurrence, that they may well call for strict liability as the best public policy."

Applying the foregoing principles of law to the artificial precipitation of rainfall, it appears that such activity falls squarely within the definition of an "ultra-hazardous activity" and that one who engages in such an enterprise would be held to account for any damage proximately resulting therefrom without regard to his actual intent or negligence, unless it were to be said that in a particular case the "necessity or utility is so great as to justify reasonable risk." Of course this would depend upon all of the surrounding circumstances which are impossible to predict.

It may be appropriate to point out at this place it has been said that the rule imposing strict or absolute liability in the case of an extra-hazardous activity does not apply if the activity is carried on in the performance of a public duty imposed

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1/ 205 C. 328, 270 P. 952, 60 ALR 475.

upon the actor as a public officer or employee or as a common carrier. 1/

There is another situation relating to possible damage by artificial precipitation which merits attention. One of the anticipated purposes for the process is to protect centers of population from the onslaught of heavy storms with resulting property damage and economic loss caused by the slowing of transportation and communications and the expense of cleaning the streets of snow, providing drainage, etc. Artificial precipitation of rain and snow upon country areas may be contemplated before the storm clouds reach the towns and cities. Proponents of such a proposal, pointing to the benefits which would be derived therefrom, might well contend that a municipality has a legal right to defend itself and its inhabitants against a common enemy, the natural elements, without liability for damage caused to others.

The right of a landowner whose land is threatened by damage from water to protect himself has been upheld under certain circumstances. It was decided at an early date that the sea is a common enemy to all proprietors on the coast and that any one of them had the legal right to protect himself from its inroads by erecting reasonable defenses, leaving the others in like manner to protect themselves against the common enemy. In reaching this conclusion the court said that "it is not enough for a plaintiff to show that he has been damaged; he must also show that a wrong has been committed by another, and in the case of an individual or of a business agency acting for others, erection of reasonable

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1/ Luthringer v. Moore, 31 Cal.2d 489, 190 Pac.2d 1.

defenses against the natural inroads of the sea is a lawful act. 1/

This principle has been applied to the waters of streams subject to periodic and extensive overflows. Thus, it has been held that riparian owners may lawfully erect and maintain levees along the banks of such streams in order to contain its waters within the natural channels, and a public reclamation district may so act in order to prevent the flooding of its lands by the natural overflow of surplus waters in times of high water without incurring liability for damage to lower riparian owners on whose lands the water consequently flows. Such damage is damnum absque injuria. 2/

However, the right to contain the water within the natural watercourse by means of dikes and levees has been said to be an aid to nature in her effort to carry the water to its ultimate destination, and the erection of a barrier across the river channel "would probably be met with the declaration that it was not the proper mode of warfare against a 'common enemy'". 3/ It has been directly held that the right of self protection "does not permit of any obstruction of or interference with the natural channel of the stream or diversion of the flow of the water in such channel. * * * The right to repel flood waters is purely one of self defense. The proprietor of land so threatened can ward off the danger by a suitable obstruction to the invasion of his

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1/ Rex v. Commissioners, 8 Barn. & C. 355. Accord: Katenkamp v. Union Realty Co., 6 Cal.2d 765, 59 Pac.2d 473.
2/ Lamb v. Reclamation Dist., 73 Cal. 125, 14 Pac. 625.
3/ Gray v. McWilliams, 98 Cal. 157, 32 Pac. 976.

land at any point upon his own premises, and by any means that does not go beyond the limits of a defensive act and become an agressive diversion of the natural flow upon other proprietors." 1/

The rule of the civil law pertaining to the right to protection against damage by surface waters has been followed to the extent that where two parcels of land are adjacent and one is lower than the other and the surface water from the higher tract has been accustomed by a natural flow to pass over the lower tract, the owner of such upper tract of land has an easement to have the water flow over the land below and the lower tract is charged with a corresponding servitude. 2/

"Flood waters escaping from natural streams are regarded as a common enemy, but in the case of surface waters having no defined channels of escape and the landowner upon which they are found being impotent to rid himself of their presence, the law wisely provides that the laws of nature shall be left untrammeled in their disposition." 3/

It follows that one has no right to obstruct the flow onto his land of surface waters where others would be injured as a consequence. 4/ "Surface waters" within the meaning of this rule, consist of surface drainage falling on or flowing from or over land before such waters have found their way into a natural watercourse. They do not include waters which were once part of a natural watercourse but which have escaped from it. These are known as "flood waters" and against them one has a right to

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1/ Weinberg Co. v. Bixby, 185 Cal. 87, 196 Pac. 25.
2/ L.A. Cemetery Assn. v. City of L.A., 103 Cal. 461, 37 Pac. 375.
3/ Gray v. McWilliams, 98 Cal. 157, 32 Pac. 976.
4/ Heier v. Krull, 160 Cal. 441, 117 Pac. 530.

protect and for that purpose to obstruct their flow onto his land even though such obstruction causes the water to flow onto the land of another, and this right has been confirmed even though the waters are not confined in or returned to the natural channel. 1/

Although the right of protection against flood waters without resultant liability to others who may be injured thereby has thus been recognized, when we seek to apply these principles to the problem at hand, we necessarily embark upon uncharted seas. The ultimate question to be determined in every case where the efforts of one person to protect himself from the elements of nature result in an injury to another is whether the action taken is reasonable in the light of all of the circumstances. "No arbitrary rule can be laid down which will govern all cases, but each case must be dealt with upon its facts, applying the rule which will be reasonable under the circumstances under the general rule that the water should be allowed as far as possible to seek its natural outlet." 2/

One who seeks to apply rules of law applicable to surface and flood waters to a diversion or obstruction of water in the clouds should perhaps take warning from the frequent refusal of our courts to blindly follow legal axioms and principles formulated to meet entirely different conditions where their acceptance would work an injury and be contrary to public policy and welfare under the conditions being dealt with. Thus it has been said by

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1/ Mogle v. Moore, 16 Cal. 2d 1, 104 Pac. 2d 785.
2/ 3 Farnham, Water and Water Rights, Section 889; Jones v. Calif. Development Co., 173 Cal. 561, 160 Pac. 823.

our Supreme Court that we will not follow either the rules of the common law or of the civil law where such rules do not meet the conditions existing in this State and where such conditions were never contemplated by the formulators of past laws. 1/ Many decisions apply the maxims "when the reason of a rule ceases, so should the rule itself", 2/ and "where the reason is the same, the rule should be the same." 3/

However, we do venture to point out that there is precedent only for protection without liability against flood waters flowing in, or which have escaped from, a natural watercourse. Also, protective measures undertaken by individuals which have previously been considered lawful have been strictly of a defensive character carried out upon the diverter's own land. Acts of aggression have never been condoned.

IV. PUBLIC PARTICIPATION, AND LIABILITY THEREFOR

Up to this point the discussion has centered upon private rights, duties and liabilities. Public rights to produce artificial rainfall and the right of a person who suffers damage as a result thereof to receive compensation for taking or damaging of property will now be considered. There will also be discussed the right of the public to regulate artificial precipitation by private individuals.

There seems no doubt that the State or a political subdivision might properly engage in the artificial precipitation of

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1/ Jones v. Calif. Development Co., supra
2/ Civil Code, Section 3510.
3/ Civil Code, Section 3511.

rain in order to augment the water supply or to make more beneficial use of natural rainfall by its redistribution or as a measure for flood control or reforestation or for other public purposes

A right of action against a public agency or its officers performing a governmental function only arises in those instances where it is authorized by law. 1/ However, the Constitution provides that private property may not be taken or damaged for public use without just compensation, 2/ and this provision is applicable to cases of damage caused by water resulting from the acts of a political subdivision in creating public improvements. 3/

Liability for taking or damaging private property for public use exists independent of negligence on the part of the public agency. 4/

"It is well settled" that damage to land caused by seepage of water from canals of an irrigation district constructed and maintained to supply water for public use gives the landowner a cause of action in the nature of eminent domain against the district. 5/ Likewise, a landowner damaged by the obstruction of a natural channel so that the natural flow in said channel is caused to leave it and overflow his land may maintain an action against the agency responsible therefor, nor may a public

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1/ Bates v. Escondido Union High School Dist., 133 Cal. App. 725,24 Pac. 2d 884.
2/ Calif. Constitution, Article 1, Section 14.
3/ House v. L.A. County Flood Control Dist., 25 Cal. 2d 384, 153 Pac. 2d 950.
4/ Tormey v. Anderson-Cottonwood Irrigation Dist., 53 Cal. App. 559, 200 Pac. 814; Eliott v. County of L.A., 183 Cal. 472, 191 Pac. 899; Kaufman v. Tomich, 208 Cal. 19, 280 Pac. 130.
5/ Powers Farms, Inc., v. Consolidated Irrigation Dist., 19 Cal. 2d 123, 119 Pac. 2d 717.

corporation collect surface water into an artificial channel and throw it upon the property of another without liability for resulting damage. 1/ The overflow of land resulting from the damming of a natural channel constitutes a direct trespass upon real property, a direct invasion of property rights amounting to a taking of it within the meaning of the Constitution. It is not a case of mere consequential damage which the landowner must protect himself against without redress. 2/

Protection of lands, harbors, and highways from flood waters and conservation of flood waters for useful purposes are essentially public although beneficial to many private individuals, and property taken or damaged for such purposes by a flood control district is "taken or damaged for public use" within the meaning of the Constitutional provision. 3/

The destruction or damaging of property is sufficiently connected with "public use" if injury is the result of dangers inherent in the construction of the public improvement as distinguished from dangers arising from the negligent operation of the improvement and in deliberately constructing a structure in furtherance of a public purpose that is "inherently dangerous to private property, the State or its agency undertakes by virtue of the Constitutional provision to compensate property owners for injury to their property arising from the inherent dangers of the public

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1/ Coniff v. City and County of San Francisco, 67 Cal. 45, 7 Pac. 41.
2/ Coniff v. City and County of San Francisco, supra.
3/ House v. L. A. County Flood Control Dist., 25 Cal. 2d 384, 153 Pac. 2d 950 (concurring opinion by Justice Traynor).

improvement or originating from the wrongful plan or character of the works". 1/

The statement in Perkins v. Blauth 2/ that if the act commanded by a municipality is in itself "inherently wrong" the municipality will be liable, has been cited as authority for holding a city liable for damage resulting from the construction of a sewer in a location and manner "likely to endanger plaintiff's property" and evidence that the sewer was so constructed supported a finding that the "location and alignment of said sewer was intrinsicly dangerous and inherently wrong". 3/

It seems that the term "inherently wrong" as used in connection with the rule imposing absolute liability upon a public agency for damages resulting from the construction or maintenance of a public improvement means that the improvement is one which is calculated to cause damage to property by its very existence without regard to negligence in its actual construction.

On the other hand, if the injury results, not from the wrongful plan or character of the work, but from the negligent manner in which it is performed, then the person so negligently acting will be held responsible. 4/

In a situation where the person injured would not have a remedy against an individual who did the act complained of, then

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1/ House v. L. A. County Flood Control Dist., supra (concurring opinion by Justice Traynor) citing Perkins v. Blauth, 163 Cal. 782, 127 Pac. 50; Kaufman v. Tomich, 208 Cal. 19, 25, 280 Pac. 130; Powers Farms Co. v. Consolidated Irrigation Dist., 19 Cal. 2d 123, 119 Pac 2d 717; Reardon v. City and County of San Francisco, 66 Cal. 492, 6 Pac. 317.
2/ Perkins v. Blauth, 163 Cal. 782, 127 Pac. 50.
3/ Kaufman v. Tomich, 208 Cal. 19, 280 Pac. 130.
4/ Perkins v. Blauth, 163 Cal. 782, 127 Pac. 50.

such injured person has no right to maintain an action against a public agency who performs the act. 1/

Compensation may not be claimed, it seems for taking or damaging private property for a public use in a proper exercise of the police power since Article 1, Section 14 of the State Constitution does not purport to create a new cause of action in favor of a property owner but merely gives him a remedy to collect damages from the State, which he formerly did not have because of the State's immunity from suit. 2/ Many attempts have been made to define "police power" and "eminent domain" and to distinguish these terms. Thus it is said by one eminent authority that valid exercise of the police power is confined to regulation designed to impose upon the owner's use and enjoyment of property the duty to so use and enjoy it as not to interfere with the general welfare of the community in which he lives; but when the legislature passes beyond mere regulation and takes or deprives one of property under the pretense of regulation, then the act becomes one of eminent domain. 3/ However, our courts have upon occasion, when dealing with public improvements, departed from the requirement that a valid exercise of the police power be confined to mere regulation and have extended the power to a taking or damaging of property in the interest of public health, safety or welfare. It has been said that having first determined that the construction of the improvement is referable to the police power, the only remaining question is whether in doing the work the proper

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1/ Archer v. City of Los Angeles, 19 Cal. 2d 19, 119 Pac. 2d 1.
2/ Archer v. City of Los Angeles, 19 Cal. 2d 19, 119 Pac. 2d 1.
3/ Lewis, Eminent Domain, Section 6, pp. 13-15.

limits of the police power have been exceeded. If not, the injured party has no right to demand compensation. In a widely cited opinion the Court says:

> " * * * we hold that the doctrine of damnum absque injuria is applicable to the prospective temporary consequential damage which it may be found will be inflicted upon the plaintiffs' lands by the future raising of a flood plane, which floods are of temporary duration and character, which raising the plaintiffs may protect themselves against, and which floods, in the progress of the work, will be taken care of so that future injury will be avoided, all this under the state's plan of vast magnitude and importance to abate, on behalf of the whole state, as well as for the benefit of private landowners, including these plaintiffs, flood conditions, which, if unchecked, would inevitably lead to the destruction of the navigability of the river and to the greater impairment and damage of all the adjacent land. Further than this it is not necessary here to go." 1/

It has long been settled law that there is an exception to the general rule that the natural drainage of surface water may not be obstructed without liability for resulting damage to property. The exception is that a city may not be compelled to compensate for injury caused to city lots as a result of the obstruction of natural drainage of surface waters across such lots as a result of changes in the grade of streets. 2/ The cited cases which apply this exception do not expressly base the right upon police power, but do assign as reasons for the City's freedom from liability the fact that such alterations in street levels are essential to the enjoyment of the lots; that it would be virtually impossible for the city to remove the water and that the remedy of the landowner is to raise the level of his lot to

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1/ Gray v. Reclamation Dist., 174 Cal. 622, 163 Pac. 1034.
2/ Corcoran v. City of Benecia, 96 Cal. 1, 30 Pac. 798, Lampe v. City & County of San Francisco, 124 Cal. 546, 57 Pac. 461.

street level. However, it is equally well settled that these considerations do not apply in the case of an obstruction by streets of surface waters flowing in a natural channel and that in such a case the landowner is entitled to compensation from the City. 1/

More recently the Supreme Court has expressly recognized that this right of a city to obstruct the drainage of surface waters by alterations in the level of streets and highways without liability is justified as a proper exercise of its police power and has extended the rule to an obstruction of surface waters by flood control levees since "the construction of improvements along a stream for purposes of flood control is no less essential to the public health and safety than the grading of streets (citing cases) and a governmental agency should no more be liable in one case than in the other for obstructing surface waters." 2/ However, the court clearly implies that the exception still holds good and that there is a duty on the part of a public agency to compensate for damage caused by an obstruction of a natural channel, although the court fails to point out why the latter type of obstruction would not be as essential to public health or safety as an obstruction of surface waters and therefore also a proper exercise of police power.

The O'Hara decision contains the following statement: "Compensation for private property taken or damaged for a public use must be made under Article 1, Section 14, only when the taking or damaging of property is not so essential to the public

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1/ Coniff v. City and County of San Francisco, supra.
2/ O'Hara v. Los Angeles County Flood Control District, 19 Cal. 2d 61, 119 Pac. 2d 23.

health, safety and morals as to be justified under the 'police power', and the injury is one which would give rise to a cause of action on the part of the owner if it were inflicted by a private person. Archer v. City of Los Angeles, et al." 1/

No case has actually applied the rule contained in the foregoing statement quoted from the O'Hara decision. On the contrary considerable uncertainty concerning its scope and proper application has been occasioned by a statement contained in a later decision of the Supreme Court, as follows:

> "Defendants contend that even if plaintiffs were damaged, the damaging occurred as the result of the exercise of police power and is damnum absque injuria. This contention is wholly without merit as there is no basis for the application of the police power doctrine to the factual situation in this case.
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> "Generally, it may be said that police power operates in the field of regulation, except possibly in some cases of emergency such as conflagration or flood when private property may be temporarily used or damaged or even destroyed to prevent loss of life or to protect the remaining property of an entire locality. There is obviously no element of regulation involved in the case at bar, and no suggestion of anything in the nature of an emergency. The damage to plaintiffs' property here involved was the result of a public improvement constructed by the state in the exercise of its power of eminent domain.
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> "While it is true that the seeming absolute protection against the taking or damaging of private property for public use provided for in section 14 of article I of our Constitution may be qualified by the police power in the area in which such power operates, it should be obvious that the police power doctrine cannot be invoked in the taking or damaging of private property in the construction of a public improvement where no emergency exists. To hold otherwise would in effect destroy the protection guaranteed by our Constitution against the taking or damaging of private property for a public use without compensation." 2/ (Emphasis added).

1/ Archer v. City of Los Angeles, 19 Cal. 2d, 19, 119 Pac. 2d 1.
2/ Rose v. State, 19 Cal. 2d 713, 123 Pac. 2d 505, 515.

In a still later case, a county and flood control district urged that they were exempt from liability for damage to property caused by the construction of dikes in and across one channel of a stream which diverted water into another channel of the same stream. Their theory was that the dikes were constructed for flood control purposes under the police power and any damage resulting therefrom was damnum absque injuria. Rejecting this contention, the appellate court first stated the often decided rule that neither a private person nor a municipal corporation or political subdivision of the State may obstruct or divert the natural flow of a stream to another's damage. The opinion then proceeds to distinguish the holding in the Archer case and quotes that part of the opinion in Rose v. State, which we have quoted. 1/

These most recent pronouncements of the courts seem to leave little or nothing of the police power - damnum absque injuria doctrine in cases of construction of public improvements regardless of how necessary they may be to public safety or welfare, with the single exception of an obstruction to the flow of surface waters. If so, we are back to the fundamental distinctions between the police power and the power of eminent domain, to wit: regulation versus taking or damaging as enunciated by Lewis and other authorities.

On the other hand, the element of negligence has been injected into the issue. Even though for a purpose deemed sufficiently essential to warrant a valid exercise of the police

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1/ Smith v. City of Los Angeles, 66 Cal. App. 2d 562, 153 Pac. 2d 69.

power, if the improvement is negligently and improperly planned, constructed, or maintained, then there is an unnecessary damage caused which has no reasonable relation to the purpose sought to be accomplished and the injury is therefore compensable, for the limits of a valid exercise of the police power have in such a case been exceeded. It is "inherently wrong". 1/

It seems reasonably certain that any impairment of a landowner's "natural right" to receive rainfall would be compensable just as compensation must always be made for the impairment or taking of a riparian or appropriative right to water for a public use. We are inclined at this time to the view that a landowner whose property is damaged as a result of artificial precipitation produced through the agency of the State or a political subdivision for a public purpose would also be entitled to compensation. However, further study of this problem is indicated. Of course we are not here concerned with the ability of a landowner to prove that the action of the State (or of a private person) in causing or attempting to cause artificial precipitation was the proximate cause of injury to his land either as a result of floods or deprivation of natural rainfall which would otherwise have been received. This is a problem of proof which in relation to the subject under consideration doubtless would be unusually difficult, at least until scientific developments make available more exact knowledge concerning the methods for producing artificial precipitation and their effect.

1/ House v. L. A. County Flood Control Dist., 25 Cal. 2d 384, 153 Pac. 2d 950.

Where a question is one of first impression, its answer depends chiefly upon matters of policy. In deciding whether in any given case compensation should be made for the taking or damaging of property for a public use, the courts are confronted with two conflicting policies - to distribute throughout the community the loss inflicted upon the individual by the making of public improvements on the one hand, and on the other the necessity for making public improvements without greatly increasing their cost. The addition of the words "or damaged" to the eminent domain clause indicates an intent to extend the first stated policy to embrace additional situations. 1/

The tendency has been too often to sacrifice the individual to the community and "it seems very difficult in reason to show why the State should not pay for property which it destroys or impairs the value, as well as for what it takes". 2/

In the area of individual rights as yet uncharted by judicial decision, a court must weigh the interests affected in each case and balance the necessity for a public improvement against the extent of damage sustained by an individual in order to determine the right to compensation. 3/

V. REGULATION

There seems to be no difficulty in sustaining the broad power of the State to regulate the artificial precipitation of

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1/ Bacich v. Board of Control, 23 Cal. 2d 343, 144 Pac. 2d 818.
2/ Sedgwick on Constitutional Law quoted in Bacich v. Board of Control, supra.
3/ Bacich v. Board of Control (concurring opinion of Justice Edmonds, supra).

rainfall both for the purpose of preventing damage to property and in order to conserve the water resources of the State. Reference to a few well settled general principles of law will suffice for present purposes.

Wherever a statute is enacted in the attempted exercise of the police power, the inquiry of the court is limited to determining whether the object of the statute is one for which the police power may legitimately be invoked and if so, whether the statute bears a reasonable and substantial relation to the object sought to be attained. It has now become firmly established that the police power of the State extends not only to the preservation of the public health, safety and morals, but also extends to the preservation and promotion of the public welfare. Although police power has not expanded, changed social, political and economic conditions have enlarged the field of conduct which may properly be subjected to regulation in order that the general welfare may be adequately protected. Proper application of the power cannot be measured by past precedents, the test is present-day conditions. 1/

Any business may be regulated to the extent and in the manner reasonably required to prevent its unreasonable interference with the welfare of the general public. 2/ The legislature can regulate and prescribe the use of a thing so that its beneficial use may be enjoyed and its detrimental use prohibited. 3/

1/ Wholesale Tobacco Dealers' Bureau v. National Candy & Tobacco Co., 11 Cal. 2d 634, 82 Pac. 2d 3.
2/ Ex parte Lasswell, 1 Cal. App. 2d 183, 36 Pac. 2d 678.
3/ People v. Ferguson, 129 Cal. App. 300, 18 Pac. 2d 741.

The police power of the State inheres in sovereignty. Any exercise of the power which has a tendency to protect life and limb is in the interest of the public weal. 1/

All property is held subject to the reasonable exercise of the police power and Constitutional provisions declaring that property shall not be taken without due process have no application to such cases. 2/

Conservation of the natural resources of the State is in the general welfare and serves a public purpose and therefore constitutes a reasonable exercise of the police power. 3/ The conservation of the water of the State is of transcendent importance. Its waters are of the very life blood of its existence. 4/

An act making it unlawful for anyone to act as a real estate broker or salesman without first obtaining a license, providing that the required license is to be issued by the Real Estate Commissioner upon written application, an annual fee to be paid for a license and giving the commissioner power to suspend or revoke a license for dishonest dealings, upon written charges being filed and an opportunity given to the licensee to be heard, making the decision of the commissioner revoking or suspending the license subject to review of the courts for abuse of discretion only, and making it a criminal offense to act as a broker or salesman without a license, has been held to be constitutional. A lawful and useful occupation may be subjected to regulation in

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1/ Raynor v. City of Arcata, 11 Cal. 2d 113, 77 Pac. 2d 1054.
2/ Chow v. City of Santa Barbara, 217 Cal. 673, 22 Pac. 2d 5.
3/ Tulare Irrigation Dist. v. Lindsay-Strathmore Irr. Dist., 3 Cal. 2d 489, 45 Pac 2d 972.
4/ Chow v. City of Santa Barbara, 217 Cal. 673, 22 Pac. 2d 5.

the public interest. The test is whether the regulations go no further than to throw reasonable safeguards in the public interest around the exercise of the right to engage in such business. If so, it is a proper exercise of the police power.

> "Where the occupation is one of which it can be fairly said that those pursuing it should have certain qualifications it is within the power of the Legislature to exact reasonable assurances of those pursuing the occupation that they do possess these qualifications."1/

Such an act as that above referred to is distinguishable from one which seeks to confer the power of granting or refusing the right requested without any specifications of the conditionsupon which it should be granted or refused. Where the power conferred is uncontrolled and unguided an objection would be good. 2/ Though an act is useful for some purposes its harmfulness to the public from its general use may be such that legislation of absolute prohibition is warranted. 3/ Laws making the right to carry on a business dependent upon first obtaining a certificate from the proper official that the business can be conducted with safety to the community, 4/ prohibiting certain businesses in specified areas, 5/ and regulating a business tending to be injurious to others 6/ have all been declared a valid exercise of police power if within the limits previously noted. Examples of other proper regulations and limitations could be multiplied almost endlessly, which is to be expected

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1/ Riley v. Chambers, 181 Cal. 589, 185 Pac. 855.
2/ Riley v. Chambers, supra, citing Los Angeles v. Hollywood Cemetery Assoc., 124 Cal. 344, 57 Pac. 153; Schaezlein v. Cabaniss, 135 Cal. 466, 67 Pac. 755; Tarpey v. McClure, 190 Cal. 593, 213 Pac. 983.
3/ Ex Parte Hixson, 61 Cal. App. 200, 214 Pac. 677.
4/ Ex Parte Maynier, 65 Cal. 33, 2 Pac. 728.
5/ Ex Parte McClain, 61 Cal. 436.
6/ Gregory v. Hecke, 73 Cal. App. 268, 238 Pac. 787.

in view of the principle previously stated that the only limitation upon the power of regulation and control vested in the Legislature is that the object be to protect public health, safety, morals or welfare, and that the means employed bear a reasonable relation to the object.

It follows that it would be entirely competent and proper for the legislature to enact reasonable regulations for the artificial precipitation of rain, including the requirement that a license be obtained from an administrative body or officer, upon such terms and conditions as are reasonably calculated to promote public health, safety, and welfare.

In addition to State regulation, artificial precipitation of rain may well become the subject of Federal regulation. Insofar as such activity would affect navigation, as by impairing the navigable capacity of a stream, the jurisdiction of the Federal Government would be paramount and when exercised might be termed exclusive. Such jurisdiction extends to any matter which may be considered regulation of commerce including flood control and watershed development. 1/

The Federal power of flood control extends to the tributaries of navigable streams and includes the power to control the entire basin of the stream. Any program of the State for water development and conservation must bow before the superior power of Congress. 2/

1/ United States v. Appalachian Electric Power Co., 311 U.S. 377, 61 Sup. Ct. 291.
2/ Oklahoma v. Atkinson, 313 U. S. 508, 61 Sup. Ct. 1050.

The Commerce Clause of the United States Constitution, broad as it has been construed to be, is not the limit of Federal jurisdiction, and it has recently been declared that "the power of Congress to promote the general welfare through large-scale projects or other internal improvement is now as clear and ample as its power to accomplish the same results indirectly through resort to strained interpretation of the power over navigation." 1/

SUMMARY

Something of the complexity and number of legal problems which might arise from artificial precipitation of rain is indicated by this progress report. Research thus far completed reveals cogent reasons for concluding that there exists a right on the part of every landowner to receive the natural benefits supplied to his land by rainfall and that this right is entitled to recognition and protection within such proper limits as may be prescribed by considerations of public policy. Subject to whatever inherent difficulties there might be in establishing the necessary facts, some degree of liability for damage caused by artificial precipitation to persons or property seems assured, and the strict rule of absolute liability may well be imposed if artificial precipitation is to be classified as an "extra-hazardous" activity. The State and its agencies may properly engage in artificial precipitation when to do so would be in the interests of public welfare. The owner of property taken or damaged by such State action would be entitled to compensation unless the taking and damaging

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1/ United States v. Gerlach Livestock Co., 70 Sup. Ct. 955.

is within the limits of a proper exercise of the police power. The State has power to regulate artificial precipitation generally, and to impose reasonable rules and regulations including a licensing system, upon all who desire the privilege to precipitate rainfall by artificial means.

Submitted by

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ADDENDUM

November, 1953

Page 1. Ben Jay Slutsky v. The City of New York, 97 N. Y. S. 2d 238, was an action by the owners of a mountain resort to enjoin rainmaking operations of the city. A temporary injunction was denied by the trial court upon the grounds plaintiffs had failed to make sufficient showing of threatened injury to justify issuance of an order restraining acts in the public interest and plaintiffs "clearly have no vested property rights in the clouds or the moisture therein."

Page 14, Note 2. Accord: Fredericks v. Fredericks, 108 Cal. App. 2d 242, 238 P. 2d 643. But see Shanander v. Western Loan & Bldg. Co., 103 Cal. App. 2d 507, 229 P. 2d 864, holding that there was no liability where damage was caused by artificial use of water under circumstances of common and ordinary usage.

In Miles v. A. Arena Co., 23 Cal. App. 2d 680, 73 P. 2d 1260, the employer of an aircraft operator who caused death of bees by crop dusting with poisonous chemicals was held liable for damages and the court declared that although dusting vegetables to kill pests is a necessary and lawful operation, the owner of the vegetables should not do the dusting or have it done under conditions which would indicate to a reasonably prudent person that damage to his neighbor would result. But see Lenk v. Spezia, 95 Cal. App. 2d 296, 213 P. 2d 47, where failure of a bee keeper to take reasonable precautions to protect his property after being warned of defendant's intention to spray a nearby field was held to constitute contributory negligence barring recovery of damages for

destruction of the bees. For other cases concerning liability for damage to crops and other property from spraying and dusting operations, see 12 ALR 2nd 436.

Page 15, Note 2. Alonzo v. Hills 95 Cal. App. 2d 778, 214 P. 2d 50.

Page 17, Note 3. Peterson v. General Geophysical Co., 185 P. 2d 56 (Cal. App.).

Page 17. Green v. General Petroleum Corp., 205 Cal. 328, 270 Pac. 952, is cited and distinguished in Shanander v. Western Loan & Bldg. Co., 103 Cal. App. 2d 507, 229 P. 2d 864, where the court refused to apply the rule of the Green case to damage caused to a tenant by water brought on the premises by artificial means by the landlord without negligence, on the grounds that the conduct was a matter of common usage and of ordinary and natural use of water.

Page 22, Note 2. Accord: Clement v. State Reclamation Board, 35 Cal. 2d 628, 220 P. 2d 897.

Page 26, Note 3. Accord: Clement v. State Reclamation Board, 35 Cal. 2d 628, 220 P. 2d 897.

Page 28, Note 2. Accord: Motzer v. Paoli, 110 Cal. App. 2d 141, 242 P. 2d 91.

Page 28, last Paragraph. See Curci v. Palo Verde Irr. Dist., 69 Cal. App. 2d 583, 159 P. 2d 674, holding that an irrigation district is not an absolute insurer against injury caused by overflow of land by water escaping from its canal, in absence of facts showing failure to use reasonable care and diligence to prevent the injury under all the circumstances. Allegations of the escape and consequent injury, by themselves,

were held insufficient to state a cause of action against the district. See also Weck v. Los Angeles County Flood Control Dist., 80 Cal. App. 2d 182, 181 P. 2d 935; Stone v. Los Angeles County Flood Control Dist., 81 Cal. App. 2d 902, 185 P. 2d 396.

Page 29, Note 2. Accord: Clement v. State Reclamation Board, 35 Cal. 2d 628, 220 P. 2d 897.

Page 33, Note 2. See Clement v. State Reclamation Board, 35 Cal. 2d 628, 641, 220 P. 2d 897, 905, wherein the California Supreme Court said:

> "The construction of the public improvement is a deliberate action of the State or its agency in furtherance of public purposes. If private property is damaged thereby the State or its agency must compensate the owner therefor (citing authorities), whether the damage was intentional or the result of negligence on the part of the governmental agency."

Page 36, Note 1. See Clement v. State Reclamation Board, 35 Cal. 2d 628, 642, 220 P. 2d 897, 905, where the court said:

> "The decisive consideration is whether the owner of the damaged property if uncompensated would contribute more than his proper share to the public undertaking."

Legal liability in connection with artificial weather modification activities has been discussed in the following periodicals:

Australian Law Journal, Vol. 26, page 527.

Albany Law Review, Vol. 14, page 204.

Vanderbilt Law Review, Vol. 4, page 332.

Georgetown Law Journal, Vol. 39, page 466.

Chicago-Kent Law Review, Vol. 29, page 150.

Catholic University Law Review, Vol. 1, page 122.

Marquette Law Review, Vol. 34, page 262.

Journal Bar Association of Kansas, Vol. 19, page 385.

APPENDIX I

ECONOMIC REPORT
ON
POSSIBLE BENEFITS OF
WEATHER MODIFICATION
OPERATIONS

September, 1952

The following discussion explores in a very preliminary fashion some of the possible results of rainmaking, or in a broader sense, weather modification. Since the subject is of an exceedingly complex nature, and for purposes of preliminary analysis, the results of weather modification operations are reduced to and evaluated in terms of economic benefits.

It should be pointed out that it has not been finally demonstrated that actual decreases or increases in precipitation can be caused to occur. However, the possibility that the weather can be modified has been presented, and it is therefore reasonable to speculate about the possible effects. It is still questionable whether the results of rainmaking would be insignificant or of economic importance. Certain positive physical effects will be assumed, however, and the economic consequences will be estimated, based upon very general assumptions.

Three possible assumptions regarding the degree of weather control due to rainmaking activities were considered, and the hydrologic and economic results are evaluated separately for each assumption. The first is explored in some detail, while the second and third are discussed briefly and then given no further present consideration.

For the first investigation, the assumption was made that precipitation might be increased by 10 per cent. This modest figure was selected for study after some consideration. There seems to be good reason to believe that local effects from cloud seeding projects are not as substantial as early claims indicated. The net results must be small or they would not be so difficult to detect. Therefore, a value of 10 per cent was selected as the measure of reasonable positive effect. Furthermore, by considering this

reasonable amount, an interesting possibility is suggested. If, in certain regions, a 10 per cent increase in precipitation was shown not to be economically justified, it would follow that any cloud seeding program useful to this area must necessarily show a greater efficiency. In addition, this limit would determine, from a statistical point of view, the amount of observational data required to establish the effectiveness or lack of effect of the program.

In this first analysis it was considered that the effect of this control would be different under a dry-farm economy than under an irrigation economy. Dry farming makes use only of the precipitation falling on the area farmed, and is directly subject to the vicissitudes of that precipitation. Dry farming is essentially a method of conserving capricious precipitation as soil moisture from season to season and from year to year. This involves the selection of crops suitable to widely varying moisture conditions, and paradoxically the number of crops adaptable to this type of culture is limited. Under irrigation, however, which is based upon artificial regulation of water supplies, a wide variety of crops can be grown. For example, irrigated agriculture in California supports more than 200 different varieties of crops. It is therefore probable that variations in rainfall will have a greater range of benefit and damage in an irrigated area than in a dry-farm region.

With these fundamental differences in mind, two separate studies were made: one to estimate the possible economic effect of 10 per cent additional rainfall on the Great Plains dry-farm lands, and the other to estimate the benefit of a similar addition to the rainfall upon the lands and tributary watersheds of an irrigation district.

The effects of a possible 10 per cent additional precipitation as it would affect a dry-farm area were explored by considering the relationships existing between average annual precipitation and per acre farm value and average size of farm in the six Great Plains states, North Dakota to Texas. These relationships were determined graphically. It was assumed that they would remain unchanged by the increase in rainfall. It is realized that there are other meteorologic, physical, and economic factors, whose joint influence might significantly alter the form of the relationships under conditions of increased rainfall. However, the effects of these factors were not assessed. In addition, it was assumed there would be no increase in dry-farm acreage due to the increased rainfall.

New farm values and sizes were determined from the graphs corresponding to the increased precipitation. The relationships appeared to be most unequivocal in the northern Great Plains states of North Dakota, South Dakota, and Nebraska. In the other states distracting effects of other influences, such as soil types and basically different culture obscured the relationships of farm values and farm sizes to fainfall.

As a first step in the analysis, the average annual precipitation for each county in the three states mentioned was interpolated from maps appearing in "Climate and Man", the United States Department of Agriculture Yearbook for 1941. For each of the three states, the average rainfall by counties was correlated with the per acre value of farm lands and buildings and with the size of farms, using the 1950 preliminary agricultural census data. Curves indicating the apparent relationships were drawn freehand.

In the analysis, all of those counties were excluded that had irrigated lands producing more than five per cent of the total agricultural production or that were closely adjacent to metropolitan areas.

As a next step, the curves were read for new farm values and sizes, corresponding to the increased precipitation. The results of the studies for the three states are shown in Table 1.

It is indicated in Table 1 that the per acre farm value of dry-farm lands in the three states might be increased by about 50 per cent, and the number of farms might be increased by about 30 per cent. In other words, if it is assumed that each farm represents one family, an increase of 10 per cent in the average annual precipitation might enable dry-farm lands in these states to support about 56,000 more families.

These values obviously represent an optimistic estimate of the benefit and no estimate has been made of the adverse unsettling economic effects which would possibly result. Use of the curves has been extended beyond the limit of observed values and the highly simplifying assumption has been made that the shape of the curves would not change. In addition, the value of farm production is a function not only of productivity but also of demand. For example, the total value of a small harvest might be greater than the total value of an abundant harvest. However, these studies indicate that an appreciable benefit would probably accrue to presently dry-farmed lands if the average annual rainfall could be increased.

TABLE 1

EFFECT OF 10 PER CENT INCREASE IN ANNUAL PRECIPITATION ON LAND VALUES AND NUMBER OF FARMS, BASED ON DIRECT CORRELATION WITH PRECIPITATION

State	Number of counties		1950 census data for dry-farm counties				Adjusted data for dry-farm counties			Increase, in per cent	
	Total	Dry-farm	Acres, in 1,000's	Value, in $1,000's	Per acre value, in dollars	Number of farms	Value, in $1,000's	Per acre value, in dollars	Number of farms	Per acre value	Number of farms
North Dakota	53	51	38,894	1,136	29.21	62,452	1,536	39.49	75,197	35	20
South Dakota	69	61	37,357	1,277	34.18	62,071	2,174	58.20	95,824	70	54
Nebraska	93	44	21,680	1,382	63.74	54,737	2,011	92.76	64,549	46	18
TOTAL OR AVERAGE	215	156	97,931	3,795	38.75	179,260	5,721	58.42	235,570	51	31

Turning to an investigation of the possible effects of a 10 per cent increase in precipitation on the total water supply of an irrigated area, an irrigation district located in the east central portion of California's San Joaquin Valley was chosen for study. Works of the district include two storage dams and a diversion dam located on a major stream of the Sierra Nevada, together with conduits to transport and serve water within the district. The drainage area above the diversion dam is about 1,550 square miles, and the 53-year mean annual flow of the stream system is about 1,900,000 acre-feet. The district generates electric power and distributes it throughout its service area, surplus power being sold to a private utility company. In addition, the district maintains drainage pumps to prevent waterlogging of lower lands. The total area included within the district is about 190,000 acres, of which about 150,000 acres are irrigated at the present time. The ground elevations of the district's service area and its tributary watershed vary between about 100 feet at the western edge of the district to about 12,000 feet at the crest of the Sierra Nevada. A wide variety of irrigated crops are grown in the district, including 80,000 acres of pasture and alfalfa, 35,000 acres of field crops, 16,000 acres of deciduous orchard, and 13,000 acres of grapes. The district lands have an average rainfall of 10 to 12 inches per year and a plentiful supply of irrigation water.

Studies of the effect of 10 per cent additional rainfall on the runoff of the tributary stream system revealed that the normal annual flow would be increased by about 15 per cent. This follows because nearly all of the additional precipitation above

the requirements of the watershed vegetation and soil mantle appears as runoff. In a dry year when only 50 per cent of normal precipitation would have occurred, a 10 per cent increase in precipitation would have resulted in a 28 per cent increase in annual runoff.

The effect upon the potential average yield of the stream system under normal conditions is the same as upon the total runoff. During the 53-year period from 1895 through 1947, the average yield of the stream would have been increased by about 15 per cent by a 10 per cent increase in rainfall.

In a prolonged period of water shortage the effect of a given percentage increase in precipitation on yield, when routed as resulting runoff through the existing conservation works, would be nearly as great in relative amount, and of considerably greater monetary value. Reservoir operation studies indicate that the existing conservation works, with a total storage capacity of about 700,000 acre-feet, including works of other districts and agencies, had a firm annual yield of approximately 900,000 acre-feet per year during the critical dry period 1922-23 through 1933-34. Similar studies indicate that 10 per cent additional precipitation would have increased the annual firm yield during this period to about 985,000 acre-feet, or an increase of about 10 per cent.

If the yield of conservation facilities is increased by 10 per cent it can be assumed that approximately 10 per cent additional lands could be brought under irrigation, or in the case of this district, about 15,000 acres. Gross farm income at the present time averages an estimated $150 per irrigated acre. Gross

income can be considered in the nature of both direct and indirect benefits to the community. Applied to the increase in irrigated agriculture this income would produce a total benefit of about $2,250,000 per year. There would also be an increase in firm power production which when based on the critical dry year of 1924 would amount to about $50,000 per year.

From the standpoint of district operation, the occurrence of any rainfall during the irrigation season from about April 1 to October 15, with the exception of a few dry years such as 1924, 1931, and 1934, would be regarded as more of a hindrance than a blessing. The district owns and operates 250 miles of main canals and laterals and 1,700 miles of ditches which serve 7,500 irrigators. A highly coordinated plan of retation of water from one canal system to another is carried out to serve the 7,500 users, and when rain occurs in any appreciable amount, irrigation is stopped temporarily, disturbing the operational plan.

During the winter season, rainfall upon the district lands is of no appreciable benefit if sufficient water falls upon the tributary watersheds and is retained by the reservoirs of the district. The saving of irrigation labor costs during the winter seasons is probably offset by increased maintenance idfficulties that result from rainy weather.

It appears that for this particular irrigated area, in view of the normal seasonal precipitation and the normally plentiful supply of irrigation water, adding 10 per cent to the seasonal precipitation would result in minor net benefit to the presently irrigated lands, except in years of critical water deficiency. Irrigation farming is most successful when the water is carefully regulated to fit particular needs which vary from farm to farm.

The lands above the district include rolling terrace lands and foothills extending to about 3,000 feet in elevation. This area embraces about 400,000 acres, of which it is estimated that about 20,000 acres are cultivated in any one year, mostly in dry-farm grain. Most of the noncultivated land is range land and dry-land pasture. The average annual rainfall is estimated to be 14 inches. This land is comparable with and somewhat equivalent to the dry-farm Great Plains states previously discussed. Heavier fall rains would stimulate germination and growth of grain and cause a heavier growth of grasses on the range land. Yields of dry-farm grain, which in this case is barley, presently range from 10 to 14 cwt. per acre in years of normal rainfall. It is estimated that the augmented rainfall would increase barley yields by as much as 75 to 100 pounds per acre. Assuming a 75-pound increase, a total increase in yield of about 17,000 cwt. would be probable for the area. This increase valued at a recent price of aboug $3.00 per cwt., would amount to $51,000, which is substantially net income.

Range land is estimated to total about 200,000 acres with an annual carrying capacity of nine-tenths animal unit month, which is defined as the amount of forage pasture just sufficient to support one animal on one acre for one month without depletion. An A.U.M. is equivalent to about four-tenths ton of alfalfa hay, and if hay is valued at $25.00 per ton, then 1 A.U.M. is equivalent to $10.00 per acre in feed value. It is believed that the carrying capacity of this range land would be increased by at least 10 per cent with a similar increase in rainfall. Therefore, the total increase in range land yield would amount to $180,000 per year.

The mountain area above the district and above the foothill lands extends from about elevation 3,000 eastward to the crest of the Sierras. Most of the land is within a national forest and is covered with coniferous timber. Deep snowpacks accumulate during the winter and spring months. Lumbering and recreational activities are the principal economic pursuits. Lumbering is the principal industry, with the mills being located below the timber growing belt. There are also numerous resort developments, most of which cater to the winter sports enthusiast as well as to the summer tourist, the fisherman, and the hunter.

The greatest need of this mountain area is not so much that of augmenting seasonal precipitation, inasmuch as it already receives in excess of 35 inches, but of providing preventive or protective measures to the great forest areas. Except during periods of flood-producing rainstorms and flood-producing snowpacks, precipitation that occurs at any time of the year is regarded as beneficial. Rains which occur during late spring serve to postpone the fire danger season, while summer rains reduce the fire hazard, and fall rains reduce or terminate the fire season. Specifically, one of the greatest hazards of the entire area is the local summer lightning storm that strikes in many places, setting fire to the forests, often in relatively inaccessible spots, and accompanied by either no rain or not enough to put out the fires. An outstanding example of this serious aspect is the case of a fire in September, 1950, when a lightning storm started fires that burned over several thousand acres of valuable private timber land before it was put out. Subsequently, in November, 1950, virtually unprecedented amounts of rain fell on the ashened bare

ground, causing severe erosion damage. The land will take years to reclaim, and the lumber operator has lost years of cutting. The Forest Service estimates that the total damage, including cost of fire fighting, erosion damage, and timber lost, amounted to $17,000,000.

The snowpack in the mountain area would be augmented if precipitation were augmented. With respect to high-elevation resort areas, additional snow would appear not to be beneficial; however, the lower-lying marginal areas that are situated below the 6,000-foot elevation would appear to benefit, for snow there is in fickle quantity, and more is always desired.

It appears that considerable caution should be exercised with respect to augmenting winter and spring precipitation inasmuch as flooding of the lowlands can easily result, aggravated erosion can take place on foothill and canyon slopes, and silt deposition in stream beds can occur, the latter effect serving to shorten the storage life of downstream reservoirs. Existing storage facilities are inadequate to regulate all floods, and the increase in runoff might be enough to overtop lowland levees and cause widespread damage to rural and urban properties and life. Flood damages tend to increase in geometric proportion to an increase in runoff, thus emphasizing the need for care in efforts to increase precipitation.

It was mentioned in the introduction that other assumptions concerning the degree of control of precipitation would be briefly considered.

For the second investigation, the assumption was made that precipitation might be increased or decreased through reasonably wide limits. There was assumed to be, however, no primary

interference with the seasonal and daily precipitation cycles or with large-scale atmospheric circulation. Precipitation would continue to occur in the winter along the West Coast and substantially in the summer in the Great Plains, and short-term droughts would endure.

With this technology the efficiency of the hydrologic control program would be greatly increased by accurate weather forecasts. The importance of this consideration cannot be overemphasized. Unless the seeding program were carefully controlled the results might be disastrous. Additional rainfall superimposed upon historic floods would have been almost entirely reflected in additional runoff with resulting higher flood crests. However, a carefully controlled weather modification program utilizing accurate weather forecasts would undoubtedly be of great value.

The yields of dry-farm crops and range lands would be increased. Water conservation and hydroelectric developments would produce larger amounts of firm water and power to serve additional customers, and many projects which are feasible from an engineering standpoint would also become economically feasible. The variability of hydrologic quantities would be reduced. Floods would be reduced and the intensity of destructive storms would be diminished. No quantitative estimates have been made of the benefits of such a program.

For the third investigation, the assumption was made that the weather of the nation might be predetermined. In this event, it would be possible to increase or decrease the precipitation in any region at any time by a predetermined amount. Such complete control requires that it would be possible to modify or direct

the general atmospheric cirulation. The pattern of general circulation of the atmosphere causes the climate, which divides the world into regions with the different kinds of natural vegetation and soils, and the different types of agriculture. Complete weather control would result in modification of these natural characteristics.

Among other things, it would become possible to reclaim both arid and excessively wet or humid regions. Large areas would be devoted to growing crops with similar water requirements so no damage would result from unseasonal rainfall. Substantial modifications would be observed in existing culture and in the natural vegetation. Deserts would disappear in regions where other requirements would make agriculture feasible. Some of the great tropical rain forests would be susceptible to settlement if the rainfall were reduced. The apparent random fluctuation of climatic and weather events could be destroyed. Selection of agricultural products to be grown in a region would be based more upon a consideration of soils and markets rather than moisture requirements. Nearly every agricultural region would be adaptable to a wider range of more valuable crops if the climatic variability were reduced.

Countless other climatic, economic, social, and physiological results and implications are immediately brought to mind, but no quantitative estimates of the possible benefits of such advanced technology have been made because it is obvious that this is not a problem for present consideration. No such control has been demonstrated but the possibility is presented to complete the picture.

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
INDIVIDUAL FLIGHTS	5-31, 5-36, 5-37

July | August | September | October | November | December

1947

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
INDIVIDUAL FLIGHTS	5-31, 5-36, 5-37
INDIVIDUAL FLIGHTS	5-32, 5-37
INDIVIDUAL FLIGHTS	4-4
ELSINORE RAIN COMMITTEE	4-5
CALIFORNIA ELECTRIC POWER COMPANY	6-9
BAKERSFIELD AIR PARK	5-32, 5-37
BIG BEAR MUTUAL WATER COMPANY	4-5
A. L. HANNAH, HEMET	4-5
LOWER SALINAS VALLEY	3-5

January | February | March | April | May | June

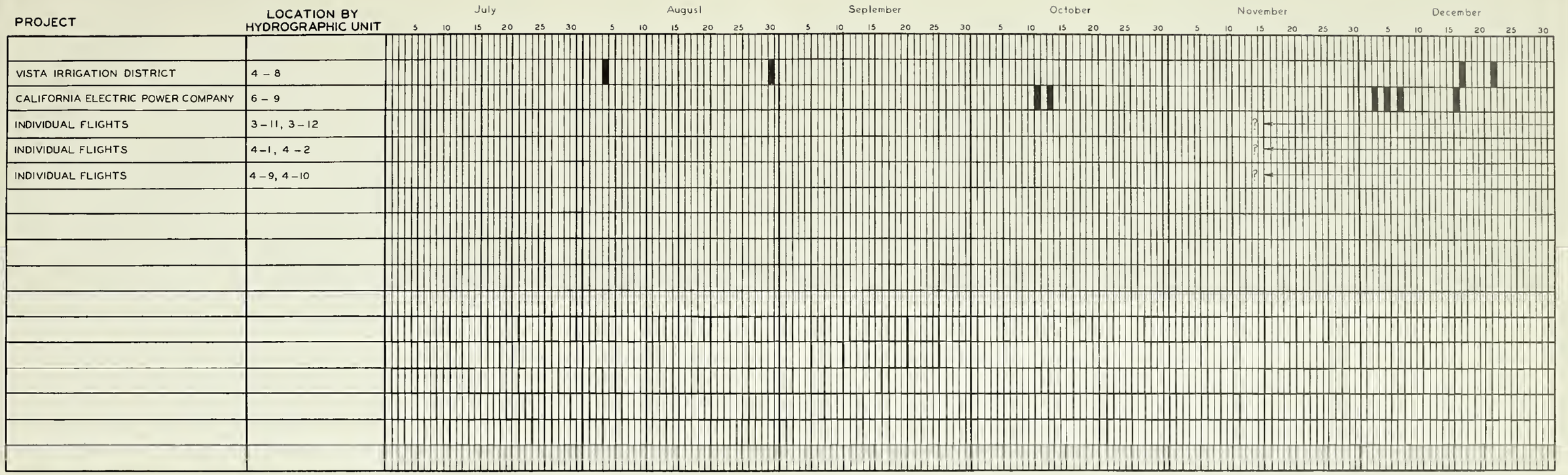
8-10 FLIGHTS ?
SEVERAL FLIGHTS
3 FLIGHTS
? SEVERAL OPERATIONS ?

1948

1947-1948
SEASON

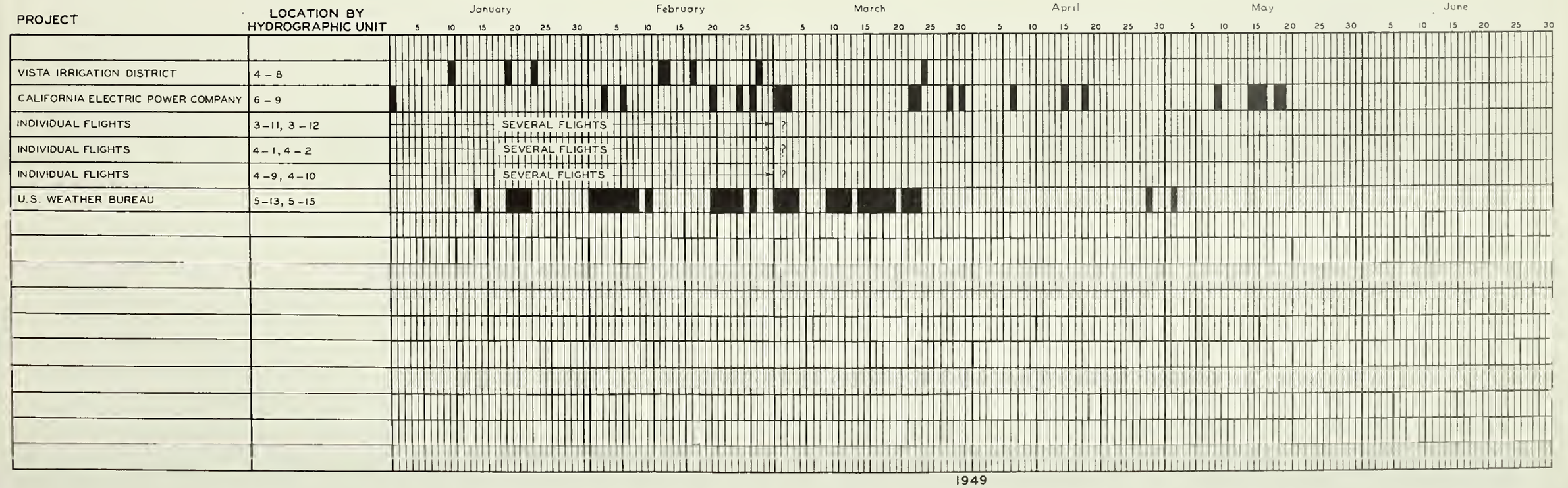
LOG OF WEATHER MODIFICATION OPERATIONS

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
VISTA IRRIGATION DISTRICT	4 – 8
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9
INDIVIDUAL FLIGHTS	3 – 11, 3 – 12
INDIVIDUAL FLIGHTS	4 – 1, 4 – 2
INDIVIDUAL FLIGHTS	4 – 9, 4 – 10



1948

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
VISTA IRRIGATION DISTRICT	4 – 8
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9
INDIVIDUAL FLIGHTS	3 – 11, 3 – 12
INDIVIDUAL FLIGHTS	4 – 1, 4 – 2
INDIVIDUAL FLIGHTS	4 – 9, 4 – 10
U.S. WEATHER BUREAU	5 – 13, 5 – 15



1949

1948 – 1949
SEASON

LOG OF WEATHER MODIFICATION OPERATIONS

DIVISION OF WATER RESOURCES

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9

July August September October November December

5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30

1949

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9
CARRISA CORPORATION	5 – 31, 5 – 36
TEMESCAL WATER COMPANY	4 – 5

January February March April May June

5 10 15 20 25 30 5 10 15 20 25 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30

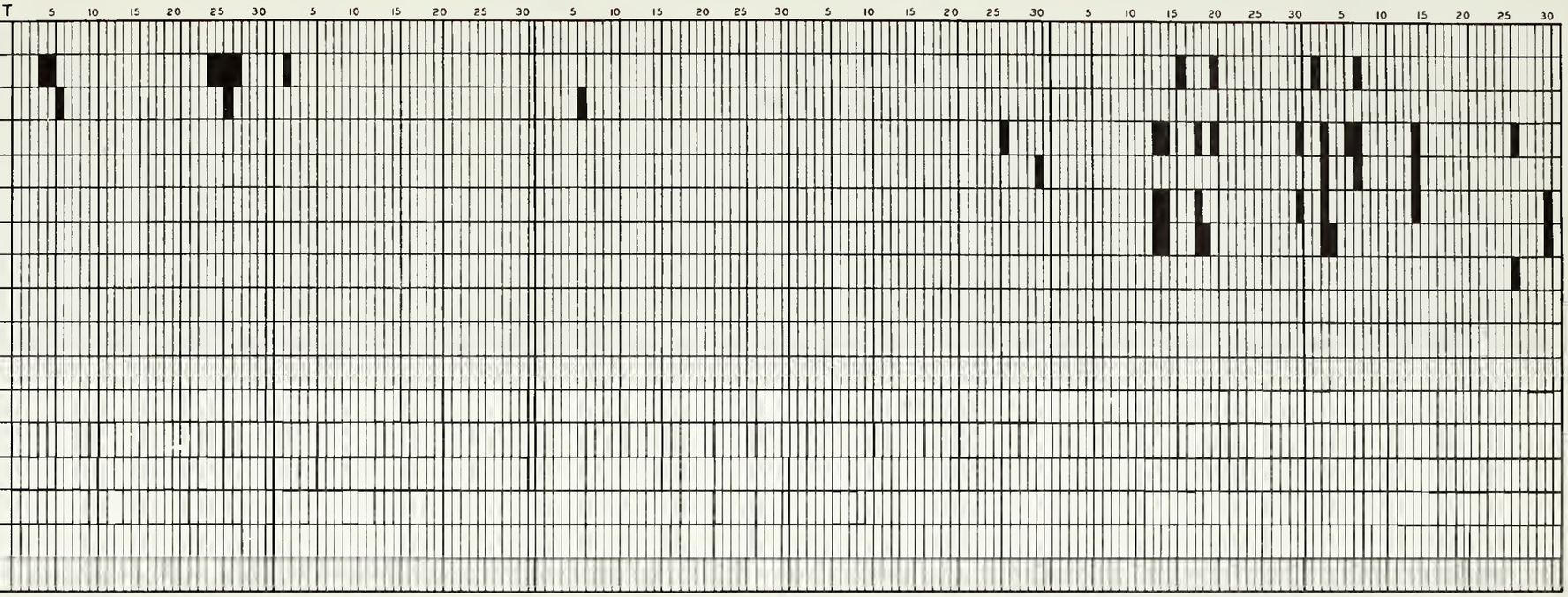
1950

1949 – 1950
SEASON

LOG OF WEATHER MODIFICATION OPERATIONS

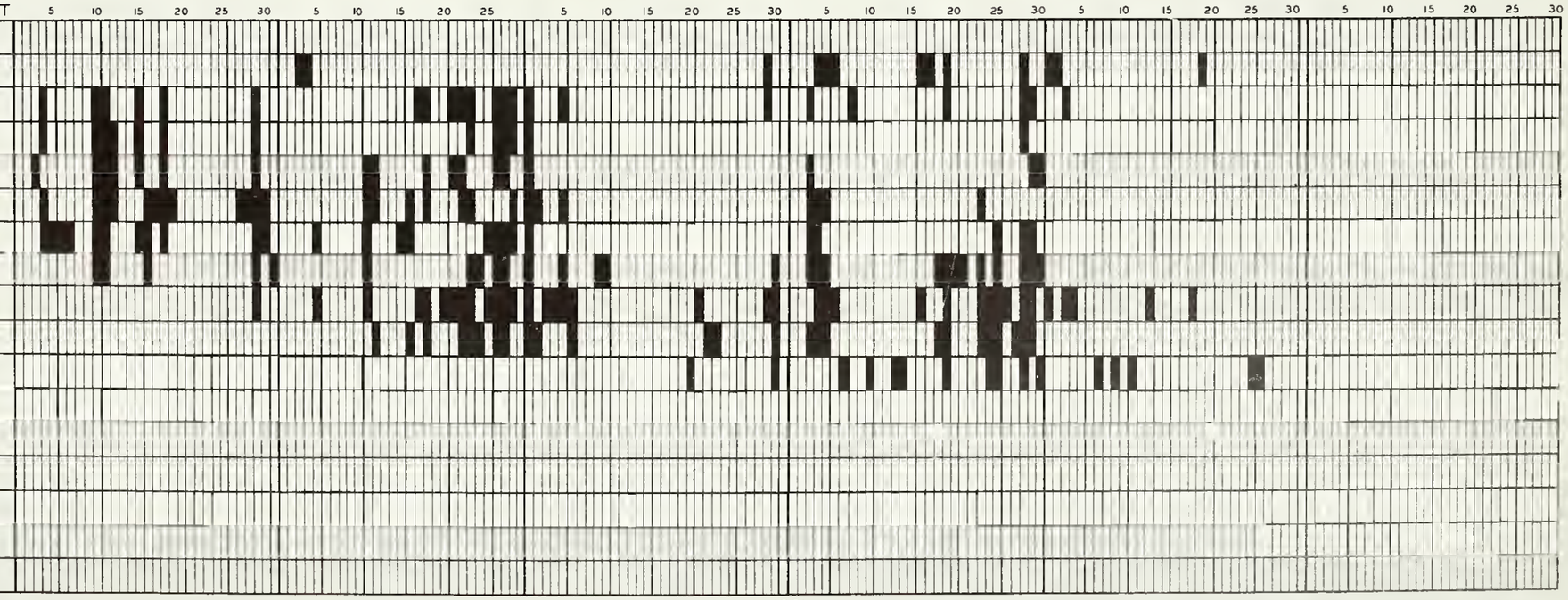
DIVISION OF WATER RESOURCES

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9
TEMESCAL WATER COMPANY	4 – 5
CARRISA CORPORATION	5 – 31, 5 – 36
KERN COUNTY	5 – 37
SOUTHERN SIERRA CORPORATION	5 – 32, 5 – 33, 5 – 38
SANTA ANA WEATHER CORPORATION	4 – 5
CITY OF SANTA BARBARA AND MONTECITO COUNTY WATER DISTRICT	3 – 12



1950

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
CALIFORNIA ELECTRIC POWER COMPANY	6 – 9
CARRISA CORPORATION	5 – 31, 5 – 36
KERN COUNTY	5 – 37
SOUTHERN SIERRA CORPORATION	5 – 32, 5 – 33, 5 – 38
SANTA ANA WEATHER CORPORATION	4 – 5
CITY OF SANTA BARBARA AND MONTECITO COUNTY WATER DISTRICT	3 – 12
ANTELOPE VALLEY WATER DEVELOPMENT CORPORATION	6 – 12
SOUTHERN CALIFORNIA EDISON COMPANY	5 – 45
CITY OF SAN DIEGO	4 – 9, 4 – 10
PLACER COUNTY FARM LABOR COOPERATIVE	5 – 13, 5 – 13

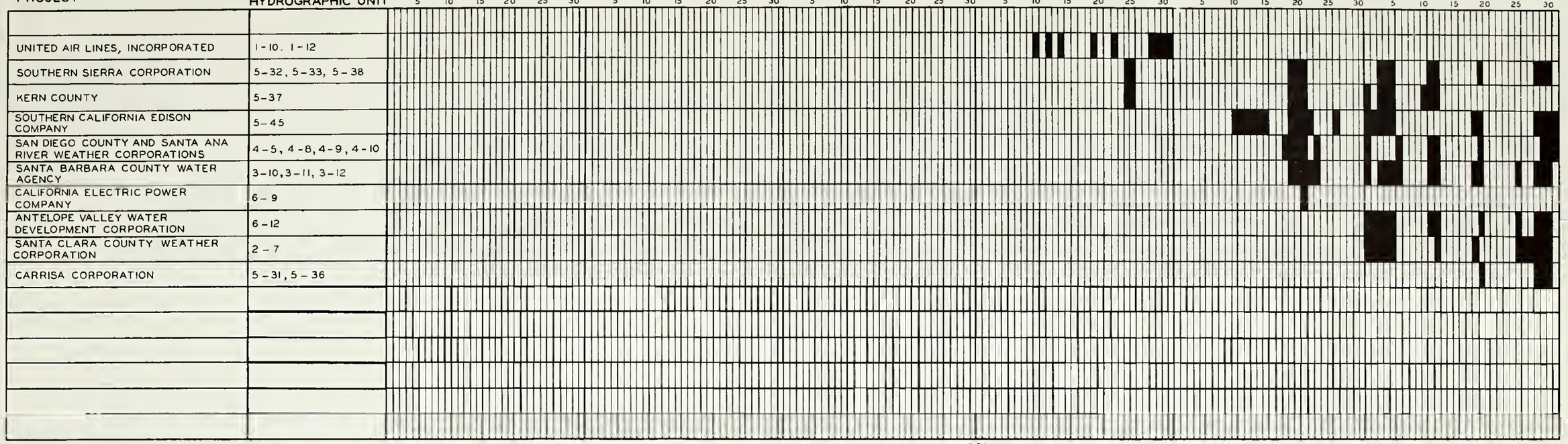


1951

1950 – 1951
SEASON

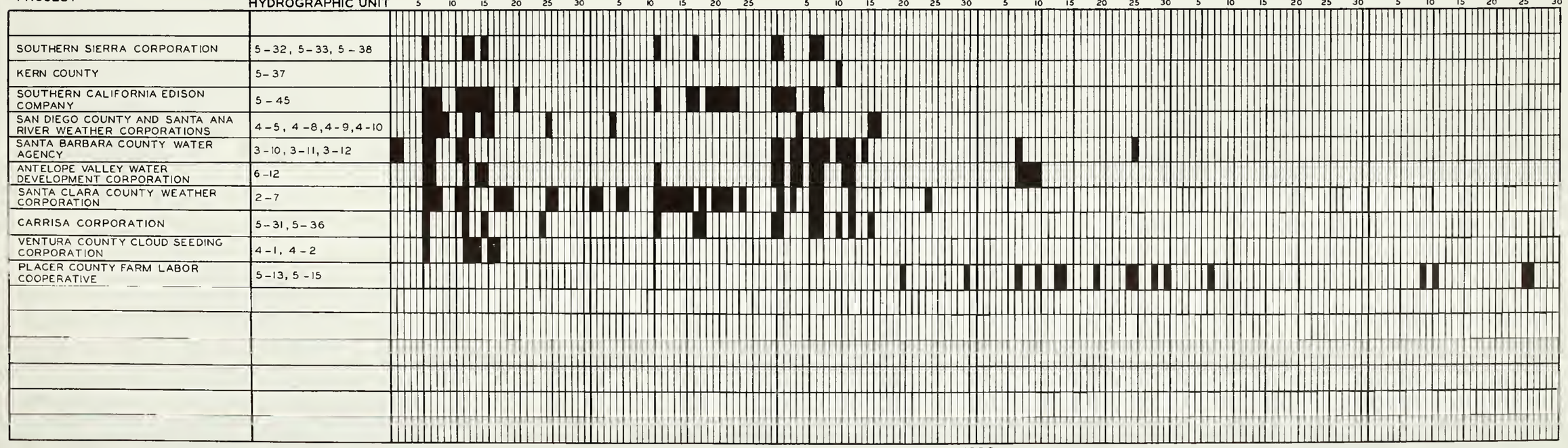
LOG OF WEATHER MODIFICATION OPERATIONS

PROJECT	LOCATION BY HYDROGRAPHIC UNIT
UNITED AIR LINES, INCORPORATED	1-10. 1-12
SOUTHERN SIERRA CORPORATION	5-32, 5-33, 5-38
KERN COUNTY	5-37
SOUTHERN CALIFORNIA EDISON COMPANY	5-45
SAN DIEGO COUNTY AND SANTA ANA RIVER WEATHER CORPORATIONS	4-5, 4-8, 4-9, 4-10
SANTA BARBARA COUNTY WATER AGENCY	3-10, 3-11, 3-12
CALIFORNIA ELECTRIC POWER COMPANY	6-9
ANTELOPE VALLEY WATER DEVELOPMENT CORPORATION	6-12
SANTA CLARA COUNTY WEATHER CORPORATION	2-7
CARRISA CORPORATION	5-31, 5-36



1951

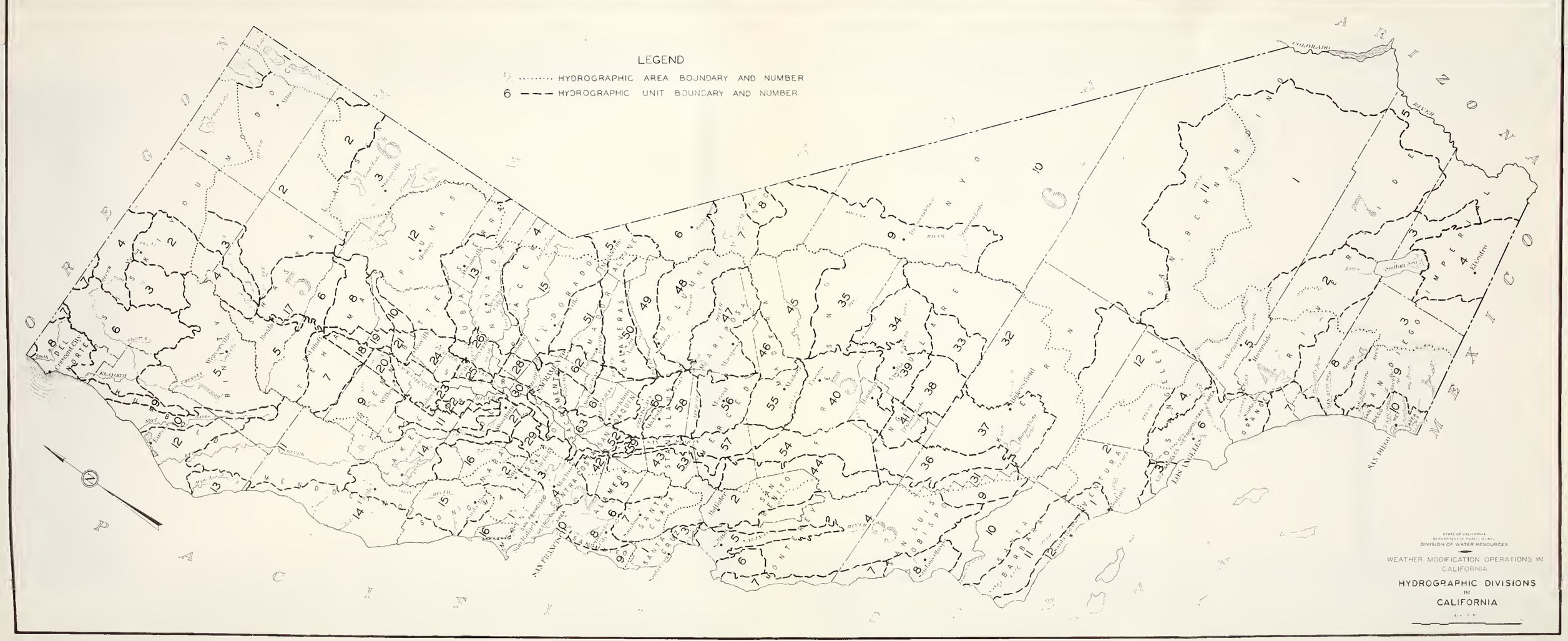
PROJECT	LOCATION BY HYDROGRAPHIC UNIT
SOUTHERN SIERRA CORPORATION	5-32, 5-33, 5-38
KERN COUNTY	5-37
SOUTHERN CALIFORNIA EDISON COMPANY	5-45
SAN DIEGO COUNTY AND SANTA ANA RIVER WEATHER CORPORATIONS	4-5, 4-8, 4-9, 4-10
SANTA BARBARA COUNTY WATER AGENCY	3-10, 3-11, 3-12
ANTELOPE VALLEY WATER DEVELOPMENT CORPORATION	6-12
SANTA CLARA COUNTY WEATHER CORPORATION	2-7
CARRISA CORPORATION	5-31, 5-36
VENTURA COUNTY CLOUD SEEDING CORPORATION	4-1, 4-2
PLACER COUNTY FARM LABOR COOPERATIVE	5-13, 5-15



1952

1951-1952
SEASON

LOG OF WEATHER MODIFICATION OPERATIONS



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WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

HYDROGRAPHIC DIVISIONS IN CALIFORNIA

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WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

TARGET AND CONTROL AREAS SANTA BARBARA COUNTY

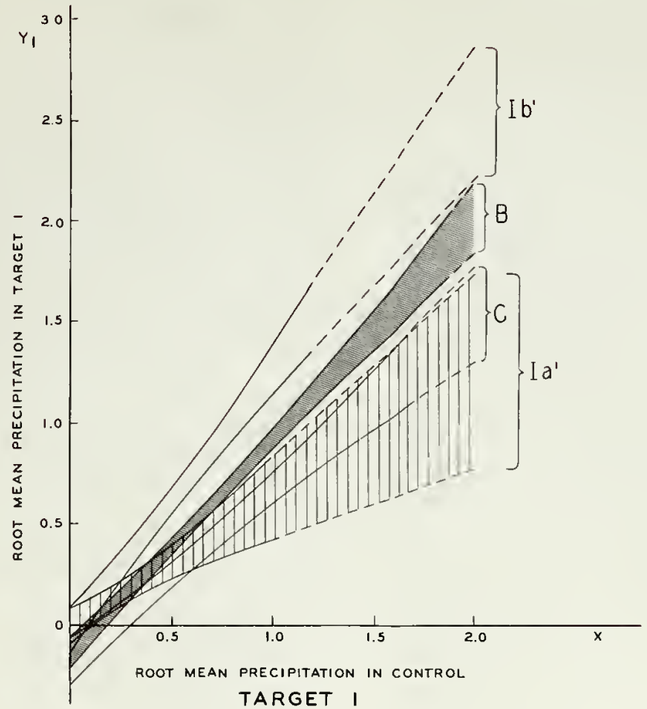
1950 - 1952

SCALE OF MILES
10 0 10

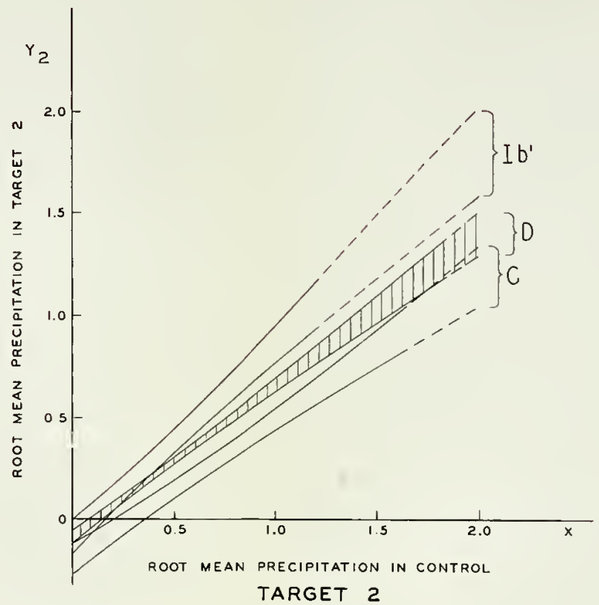
LEGEND

▲2 CONTROL PRECIPITATION STATION
Δ5 TARGET PRECIPITATION STATION
5 TARGET AREA

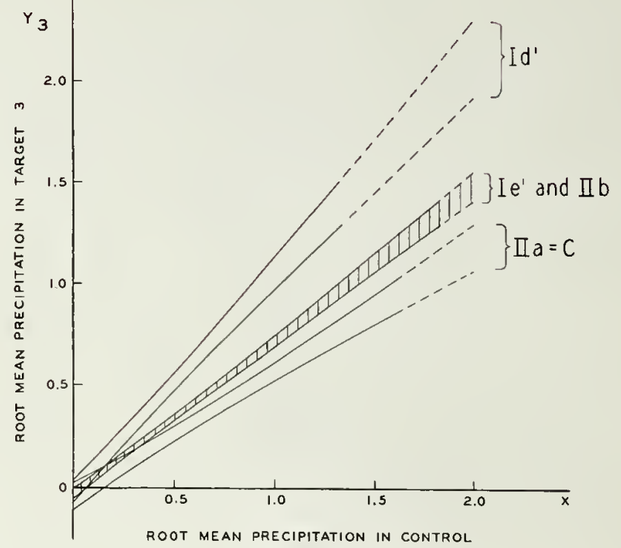
FRESNO
KINGS
TULARE
KERN
SAN LUIS OBISPO
MONTEREY
SANTA BARBARA
VENTURA
PACIFIC OCEAN
SAN JOAQUIN VALLEY
SALINAS RIVER
CUYAMA RIVER
SANTA MARIA RIVER
SISQUOC RIVER
SANTA YNEZ RIVER
CLARA RIVER
SANTA LUCIA RANGE
SIERRA MADRE MOUNTAINS
SANTA YNEZ MTS
TEMBLOR RANGE
CALIENTE RANGE
PANZA RANGE
LOS OSOS VALLEY
SANTA MARIA VALLEY
CASMALIA HILLS
SOLOMON HILLS
PURISMA HILLS
LOMPOC
SANTA MARIA
SAN LUIS OBISPO
PT. PIEDRA BLANCAS
PT. BUCHON
SANTA CRUZ ISL.
SANTA ROSA ISL.



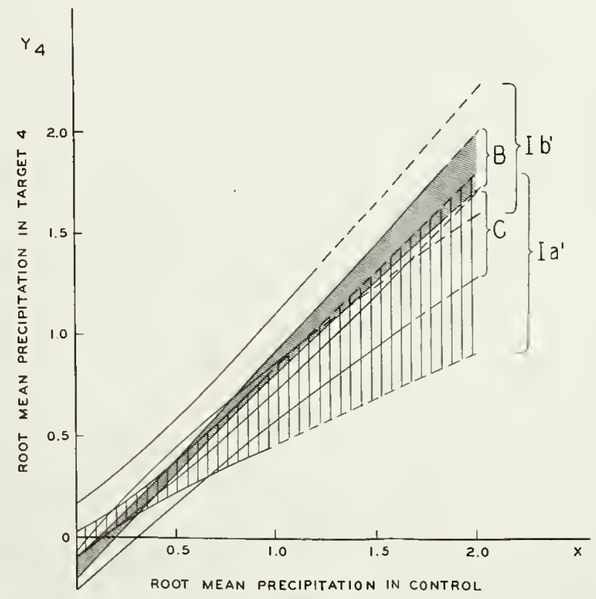
TARGET 1



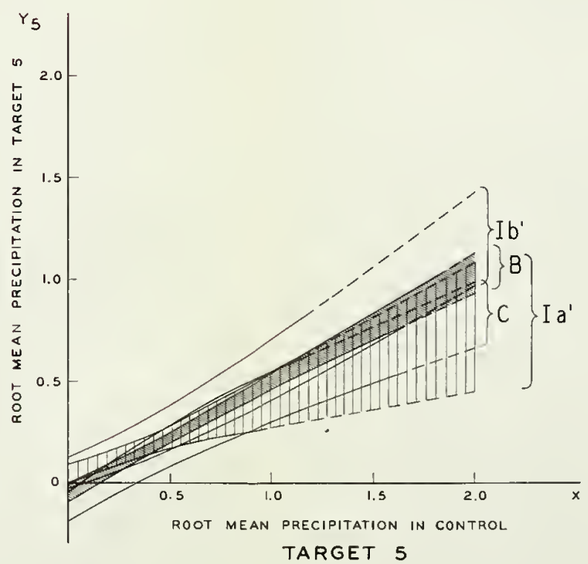
TARGET 2



TARGET 3



TARGET 4



TARGET 5

LEGEND

SOLID LINE BASED ON ACTUAL DATA

DASHED LINE ESTIMATED EXTENSION

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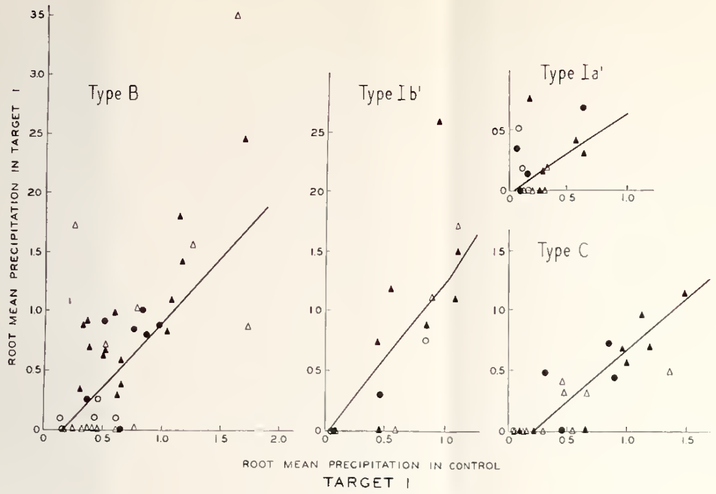
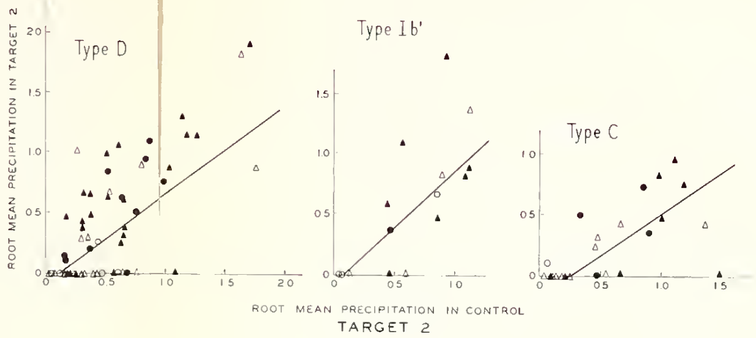
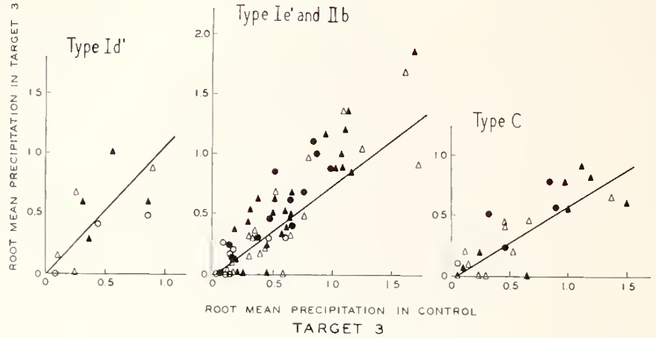
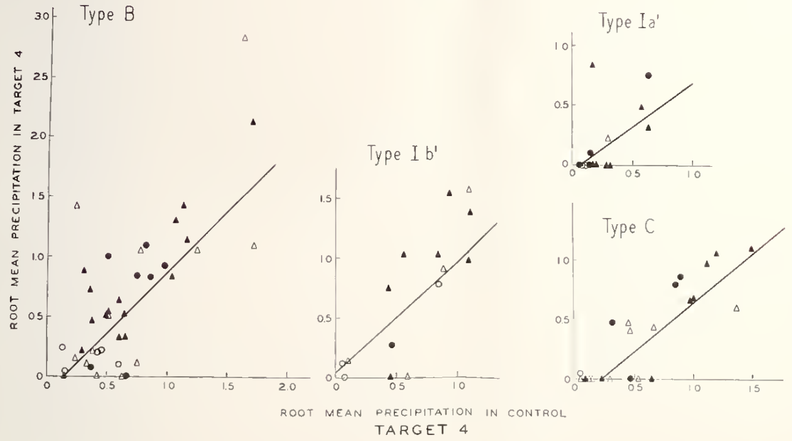
WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

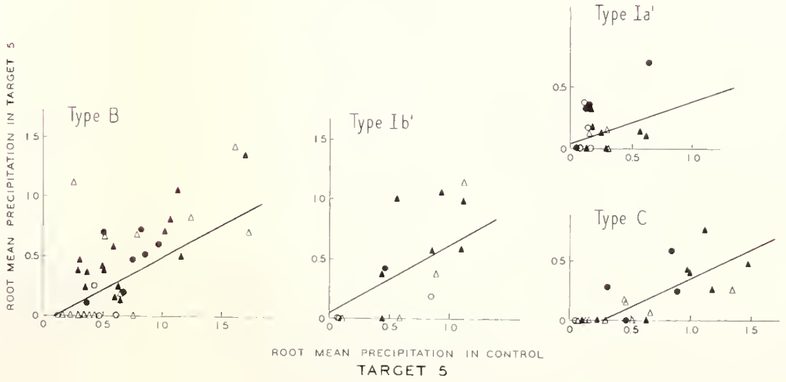
SIMULTANEOUS 50 PERCENT CONFIDENCE INTERVALS FOR STORMS OF SPECIFIED CLASSES BY TARGETS IN SANTA BARBARA COUNTY











LEGEND

1950-51	1951-52-53	
●	▲	SEEDED
○	△	UNSEEDED

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WEATHER MODIFICATION OPERATIONS IN CALIFORNIA

COMPARISON OF STORMS DURING SEEDED PERIOD WITH HISTORICAL REGRESSIONS FOR SANTA BARBARA COUNTY

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